

Magnetic Field Configuration in the Magnetotail near $60 R_E$

by

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Abstract

The magnetic field line configuration in the geomagnetic tail near $60 R_E$ is examined on the basis of nearly three years of magnetometer data from the lunar orbiting Explorer 35 satellite. The magnetotail field line characteristics inside the plasma sheet and in the high latitude tail, i. e. outside the plasma sheet, are separately examined. In the high latitude tail the magnetic field lines systematically diverge in both longitudinal (east-west) and latitudinal (north-south) directions; the divergence angle between field lines near the dusk flank and those near the dawn flank is about 18° , but the divergence along the Z-direction is only about 8° . The degree of divergence is found to be greater in the evening side than that in the morning side, and greater in the northern than in the southern tail. Inside the plasma sheet, the field lines are greatly deviated away with respect to the sun-earth line and the spatial distribution of the field line deviation does not have any systematic tendency. The average longitudinal and latitudinal deviation is about 20° and 17° , corresponding to the average $|B_Y|$ and $|B_Z|$ of 1.9γ and 1.7γ , respectively. The geomagnetic activity dependence of the field line configuration is also examined and no drastic difference is found during different K_p periods.

I. Introduction

The magnetic field observations by IMP-1 satellite have revealed the basic structure of the magnetotail which consists of two oppositely directed lobes of magnetic field lines, one towards the earth in the northern tail and the other away from the earth in the southern tail (Ness, 1965). Between these two regions is the plasma sheet, a slab of plasma with a finite β value. The mid-plane of the plasma sheet coincides approximately with the neutral sheet which is formed by a thin current sheet, separating the oppositely directed field line fluxes, to sustain the magnetotail. Characteristics of the cislunar magnetotail field have since been explored extensively by IMP and AIMP series of satellites. The magnetic field is usually very stable and oriented approximately along the Sun-Earth line; the aberration angle of the magnetotail axis, with respect to the Sun-Earth line is about 3.1° due to the motion of the Earth around the Sun and/or the non-radial solar wind flow associated with the corotational motion of the interplanetary plasma with the Sun (Ness et al., 1967; Behannon, 1968, 1970; Behannon and Ness, 1968; Mihalov et al., 1968; Sonett et al., 1969). The divergence of magnetotail field lines away from the magnetotail axis was indicated by Explorer 33 and 35 magnetic field measurements (Mihalov et al., 1968; Behannon, 1970). However, it is recently reported that the field lines inside the plasma sheet are highly fluctuating and deviate considerably from the Sun-Earth line (Ness et al., 1967; Mihalov et al., 1968, 1970; Behannon, 1970; Hruska and Hruskova, 1970). Furthermore, the plasma sheet in the magnetotail undergoes frequently large-scale temporal variations, for

example during substorms. If this is indeed the case, it is important to attempt to separate spatial (with respect to the neutral sheet) and temporal variations.

In this paper, the configuration of the tail magnetic field lines both inside and outside of the plasma sheet at the lunar orbiting distance is separately examined by using nearly three years of magnetic field observations from the Explorer 35 satellite. In addition to the two-dimensional (YZ plane) mapping of the field line spatial distribution perpendicular to the magnetotail axis, temporal changes of the field line configuration are also studied for different geomagnetic activities represented by the K_p index; seasonal variations are also investigated.

II. Analysis

The once every synodical month magnetotail crossing by the lunar orbiting Explorer 35 provides the most extensive magnetic field measurement in the distant magnetotail. The magnetic field data used here are obtained from the on-board NASA Ames magnetometer, averaged over either 7 or 8 telemetry sequences (approximately every 10 minutes) and this set of data has been used and described in earlier studies of the plasma sheet geometry (Meng and Mihalov, 1972a, b). In order to avoid possible inclusion of the magnetic field observations outside the magnetotail in the magnetosheath region, measurements obtained within the range of $-21 R_E \leq Y_{SM} \leq 24 R_E$ and $-18 R_E \leq Z_{SM} \leq 18 R_E$ are used here. The asymmetry along the Y_{SM} axis is due to the tail axis aberration. There are about 16,000 10-minute magnetic

field averages from thirty-four Explorer 35 magnetotail crossings between July 22, 1967 and March 24, 1970. (See Table 1 of Meng and Mihalov, 1972a, for detailed date of crossings.)

In the high latitude tail lobes the magnetic field lines align approximately with the Sun-Earth direction; whereas inside the plasma sheet, their direction is highly fluctuating and is not simply directed toward or away from the sun. A binary test was utilized to divide the magnetic measurements into these two different regions. Two criteria are used independently to label magnetic field observations in the high latitude magnetotail region (outside the plasma sheet): (1) when more than 90% of the individual vector samples, within the 10-minute interval, are directed parallel to the Sun-Earth line between $-13.0^\circ \leq \theta_{SM} \leq 13.0$ and $-25.0^\circ \leq \varphi_{SM} \leq 15.0^\circ$ (or $158.0^\circ \leq \varphi_{SM} \leq 195.0^\circ$); (2) when the variance over the 10-minute period, along the average magnetic field, is less than 0.8γ . Otherwise, the observed magnetic field is defined as those detected inside the plasma sheet (Meng and Mihalov, 1972a). Results from both criteria are similar, thus only those using criterion (1) will be presented in this paper.

By ignoring the ellipticity of the moon's orbit and the variation of the Explorer 35 orbit along the Sun-Earth line (X axis), the magnetic measurements are "mapped" onto two dimensional (YZ) plane. The cross section of the magnetotail from $Y = +24 R_E$ to $Y = -21 R_E$ and from $Z = +18 R_E$ to $Z = -18 R_E$ was divided into 180 square areal elements with a $3 R_E$ by $3 R_E$ size. Figure 1 shows the distribution of the number of data points in each areal element, in which the

upper number is for those detected in the high latitude tail and the lower number for those in the plasma sheet. It is important to note that in this paper, the terms "high latitude tail" and "plasma sheet" refer to the two magnetotail plasma regimes and do not refer to the averaged geometrical locations in the magnetotail; thus, the field lines of "high latitude tail" can sometimes be detected at locations adjacent to the expected neutral sheet location ($Z_N = 0$ or $Z_{SM} = 0$) and similarly, the field lines of the "plasma sheet" can sometimes be observed far away from the equatorial region of the magnetotail.

III. High latitude tail region

The total of about 1200 hours of high latitude tail magnetic field observations are evenly distributed either in the northern (+Z) versus southern (-Z) or the morning ($-21 R_E < Y_{SM} < 3 R_E$) versus evening ($3 R_E < Y_{SM} < 24 R_E$) parts of the magnetotail (see Figure 1). Within each areal element, averages of the following magnetic field components in the solar magnetospheric coordinates are obtained: (1) the field magnitude (B); (2) latitude angle (θ) which is the north-south angle between the field vector and the solar magnetospheric equator; (3) longitude angle (ϕ) which is the east-west angle between the magnetic vector and the Sun-Earth line on a plane parallel to the solar magnetospheric equator; (4) X-component (B_X); (5) Y-component (B_Y); (6) Z-component (B_Z), which are three field components in the solar magnetospheric coordinates, together with their absolute values. Averages over each column and row are also calculated for examining the longitudinal (along Y_{SM}) and latitudinal (along Z_{SM}) distributions

of these field parameters. In the spatial distributions of these quantities on the cross section plane of the magnetotail, the geometrical location of each magnetic field measurement is expressed in the solar magnetospheric coordinates and two neutral sheet coordinates, defined by Murayama (1966) and Russell-Brody (1967). These three coordinate systems give essentially similar spatial distributions of the field parameters; therefore, only Murayama's neutral sheet coordinates are presented here.

A. Spatial distribution

The average of the magnetic field magnitude in the high latitude tail is 10.8γ and the scatter with respect to this value is illustrated in Figure 2. Figure 3 shows that the distribution of the field magnitude (B) is not uniform over the tail cross section. Longitudinally, the magnitude in the central part of the tail ($-9 R_E < Y_{SM} < 9 R_E$) is higher than that near both flanks ($9 R_E < Y_{SM} < -9 R_E$), and, latitudinally, the field intensity in the southern tail is higher than that in the northern tail.

The spatial distribution of B_X (the average of the field X-component) and $|B_X|$ (the average of the absolute value of B_X 's) at each areal element is illustrated in Figure 4, in which the B_X (the upper value in each element) is positive in the positive Z-region and negative in the negative Z-region, except for a few irregularities, corresponding to a sunward and anti-sunward directed field in the northern and southern part of the tail, respectively. It is interesting to compare the value of B_X with that of $|B_X|$ at each areal element;

a smaller value of B_X indicates that the field with both polarities in X-direction were observed. For example at $6 R_E < Y_{SM} < 9 R_E$ and $3 R_E > Z_N > 0 R_E$, B_X of -0.15γ and $|B_X|$ of 10.56γ means that approximately equal numbers of sunward and anti-sunward directed fields were observed here. Areal elements with different values of B_X and $|B_X|$ are limited in regions above $Z_N = -3 R_E$ and below $Z_N = +6 R_E$, due to temporary changes of the neutral sheet configuration, and/or latitudinal motions of the tail. The average $|B_X|$ of the high latitude tail over the entire observable cross section is 10.64γ and its distribution is slightly non-uniform, similar to that of B.

Figure 5 shows the distribution of the tail field deviation along the east-west direction (Y_{SM} axis). The lower value in each element is the observed B_Y which is the deviation with respect to the Sun-Earth line (X_{SM} axis) and the upper B_Y includes the tail axis aberration correction of $\pm 0.6\gamma$ in $\pm Z$ region corresponding to an average field of 11γ and an aberration angle of about 3.1° . It is interesting to note that after the correction, B_Y in the northern-dawn quadrant changed from negative to positive and this corrected spatial distribution of B_Y (the east-west longitudinal deviation of the tail field with respect to the aberrated tail axis) is qualitatively consistent with the configuration of field lines for a diverging magnetotail, namely negative B_Y 's in the northern-dusk and southern-dawn quadrants and positive ones in the northern-dawn and southern-dusk quadrants.

The distribution of $|B_Y|$, which represents the magnitude of

the longitudinal deviation from the Sun-Earth line, is not uniform. In the dusk part of the tail, $|B_Y|$ gradually decreases from about 2γ near the flank to about 1γ at the center of the tail; however, in the dawn side it maintains a constant value of about 0.8 or 0.9γ . In latitude, $|B_Y|$ has a greater value of 1.8γ at $Z_N \approx \pm 18 R_E$ than that near $Z_N \approx 0$ of 1.2γ .

In order to see quantitatively the longitudinal divergence of the tail field along the Y_{SM} direction, the distribution of the longitudinal angle $|\varphi|$ is shown in Figure 6, in which $|\varphi|$ is the absolute angular deviation of φ with respect to 0° and 180° axis. Along the Y-direction, $|\varphi|$ is gradually decreasing from 12° at $Y_{SM} \approx 24 R_E$ to 4.5° at $Y_{SM} \approx -3 R_E$, indicating an approximate divergence rate of about 1° per $3 R_E$ or higher from the tail center to the evening side of the magnetopause. However, in the morning side of the tail, $|\varphi|$ has nearly a constant value of 4.5° , indicating that the magnetic field lines may not deviate as much as those in the evening side and that the divergence is about 7.6° with respect to the aberrated axis of the magnetotail. Along the Z-direction, $|\varphi|$ does not distribute symmetrically in Z_N , with the smallest $|\varphi|$ near $Z_N \approx -5 R_E$, and it is always larger in the northern tail than in the southern. This tendency indicates a greater degree of longitudinal divergence in the northern part of the tail than in the southern for the data sampled during winter and summer, respectively.

The latitudinal (north-south) divergence of the magnetic field lines in the meridian planes is illustrated by the distribution of B_Z component and latitude angle θ in Figure 7. The profile of averaged

θ over different Z_N values shows that θ is smoothly decreasing from about $+3^\circ$ at $Z_N \approx 0 R_E$ to about -3° at $Z_N \approx \pm 15 R_E$; and the tail field line divergence exists, on the average, in regions above $Z_N \approx 6 R_E$ and below $Z_N \approx -12 R_E$, indicated by negative values of B_Z 's and θ 's. Along the Y_{SM} axis, θ is -1.5° near the dusk flank and gradually increases to $+3^\circ$ near the dawn flank, revealing a non-uniform latitudinal divergence along Y , even though the $|\theta|$ has an almost constant value of about 4° over the whole tail cross section. In the magnetotail, the convergence or divergence of magnetic field lines with respect to the magnetotail equatorial plane is represented by a positive or negative θ angle, respectively; thus, the latitudinal divergence can also be determined from the distribution of the occurrence frequency for negative θ angles (Figure 8). Between $Z_N = +3 R_E$ and $-3 R_E$, only 20% of the observed field lines diverges, gradually increasing to 70% at $|Z_N| \approx 18 R_E$. Thus, the field lines are essentially converging near the magnetotail equatorial plane, but they have a greater tendency of divergence at a greater distance from the neutral sheet. Along the Y -direction, about 60% of the θ angles are negative near the dusk flank and slowly decreases to only 30% near the dawn flank, corresponding to a greater degree of the latitudinal (north-south) divergence in the dusk side. Therefore, the field line divergence, in both longitudinal (east-west) and latitudinal (north-south) directions, is larger in the evening part of the tail than in the morning side.

B. Temporal variations

There are two major causes for the magnetotail configurations

to change: the solar wind (and its related geomagnetic activity) and the season of a year. Since the comprehensive solar wind conditions are not available during these 34 tail crossings, the magnetic field measurements in the high latitude tail lobes are divided either into the low K_p ($K_p \leq 1+$) and high K_p ($K_p \geq 2-$) subgroups according to the geomagnetic activity, or three seasonal subgroups, equinox, summer and winter. The ratio of the number of data points between low K_p and high K_p groups is about 3 to 2 and seasonally is about 2:1:1.

1. K_p dependence

The most obvious tail field variations associated with the K_p index is the field magnitude. The magnitude (B) (see Figure 2) and the absolute values of two field components ($|B_x|$, $|B_z|$) are about 87% for low K_p ($\leq 1+$) values and 120% for high K_p ($\geq 2-$) values with respect for all K_p values. Angularly, the average of the latitudinal angle (θ) over the entire cross section is quite different (0.4° for low K_p and 1.2° for high K_p), but $|\theta|$ is similar ($\sim 4.3^\circ$) for different K_p values (see Table 1). On the other hand, from the distributions of the $|\varphi|$ along the Y-direction (see Figure 6) it is found that there are no significant differences between high K_p and low K_p groups, indicating statistically no change in the longitudinal (east-west) angle during a moderate or an intense geomagnetic activity.

2. Seasonal variations

In studying seasonal variations of the magnetotail at the lunar orbit, it is important to note that due to the intrinsic limitation of the

lunar orbit, the Explorer 35 observations are confined to the southern part of the tail centered at $Z_N \approx -8 R_E$ in summer months, and to the northern tail centered at $Z_N \approx +8 R_E$ in winter months. In summer, due to the presence of more high K_p observations, the average field magnitude is higher (at 12.5γ) than the all year average of 10.8γ , and so is the absolute value of its components (B_X, B_Y, B_Z). Directionally, $|\theta|$ does not show any significant seasonal variations; however, averaged $|\varphi|$ is smaller in summer ($\sim 6.3^\circ$) than in winter ($\sim 7.9^\circ$) and the profiles of $|\varphi|$ distribution (Figure 9) are different between two solstices, namely in the evening side $|\varphi|$ values are about 3° or greater in winter than in summer. This apparent seasonal difference is actually due to a spatial variation in $|\varphi|$ distribution between northern and southern tail lobes, since the data from equinoctial months also show that $|\varphi|$ is larger in the northern-dusk quadrant than in the southern-dusk. During equinox, Explorer 35 measurements are centered at $Z_N \approx 0 R_E$ and the observed distributions of high latitude tail lobe field line configuration are essentially the same as those without seasonal and K_p separation.

The most interesting feature of the high latitude field lines is their divergence with respect to the tail axis. It is clearly illustrated by the longitudinal $|\varphi|$ angles observed during summer months in the southern tail lobe. Figure 10 shows the average φ value at each $3 R_E$ wide Y_{SM} interval; together with the φ angle longitudinal distribution detected between $-9 R_E \leq Z_N \leq -6 R_E$. The divergence angle between the field lines near the dusk and dawn flanks of the tail is about 18° and the approximate divergence rate is

larger ($\sim 0.7^\circ$ per R_E) in the dusk side than that ($\sim 0.3^\circ$ per R_E) in the dawn side. This gives a model configuration of the field lines in the high latitude tail region along the azimuthal direction from $\varphi = 168^\circ$ at $Y_{SM} \approx 18 R_E$ gradually increasing to 180° at $Y_{SM} = 0$ and to 184° at $Y_{SM} \approx -18 R_E$ in the southern tail.

The characteristics of the magnetic field lines in the high latitude tail region near $60 R_E$ observed by Explorer 35 are summarized in Table 1. It clearly indicates that the magnetic field lines diverge in both longitudinal (φ) and latitudinal (θ) directions. The degree of divergence is greater in the evening side of the magnetotail than that in the morning side, and greater in the northern tail than in the southern. The divergence angle between field lines near the dusk flank and those near the dawn flank is about 18° , but the divergence angle along the Z-direction is only about 8° ; thus, the rate of divergence is larger along the east-west direction than along the north-south direction. It is also found that the configuration of the high latitude magnetic field lines is not affected by geomagnetic activity (or the solar wind pressure variations).

IV. Plasma sheet

There are about 1500 hours of the Explorer 35 magnetic field measurements which are taken inside the plasma sheet at the lunar orbit. Data sampling points are evenly distributed either in the northern versus the southern or the dusk versus the dawn sides of the magnetotail as shown in Figure 1. The magnetic field in the plasma sheet is characterized by the diamagnetic effect of plasma, the angular

deviations away from the Sun-Earth alignment and above all, the frequent large fluctuations. The scatter of data with respect to the average (i. e. arithmetic mean) of each field parameter is rather large as illustrated by the percentage distribution of three magnetic field components in Figure 11. It is found that the average of field magnitude (B) over the entire tail cross section of the plasma sheet is 7.81γ which is about 30% less than that of the high latitude tail lobe due to the plasma diamagnetism. The average of the latitudinal angle (θ) is 10.57° , indicating a large angular deviation from the solar magnetospheric equatorial plane, and the standard deviation with respect to the average is 19.29° , which is almost four times greater than that observed in the high latitude tail, corresponding to a large angular fluctuation inside the plasma sheet.

A. Spatial distribution

The spatial distribution of the magnetic field components observed within the plasma sheet is not usually systematic as that observed outside the plasma sheet is; for example, in the distribution of the field magnitude (B), there is no indication for small B 's located near the equatorial plane or any other trends in the distribution. Similarly, the field strength in the X-direction, $|B_X|$, is randomly distributed with an average of 6.73γ . However, except for a few anomalous points, the direction of the averaged magnetic field X-component, B_X , within the plasma sheet is sunward (positive) in the northern tail and anti-sunward (negative) in the southern tail as shown in Figure 12; and the mean value of B_X over the entire cross

section is almost zero (0.04γ), indicating balanced observations above and below the neutral sheet. Values of B_X (upper one in each block) and $|B_X|$ (lower one) observed inside the plasma sheet are different in each areal element; this is not the case in the high latitude tail. This means that the neutral sheet, separating two oppositely directed field line regions, is not stably located adjacent to the calculated $Z_N = 0$ location and is frequently observed even at a distance of more than $10 R_E$ away from the expected location.

The B_Y values are almost all negative over the entire cross section with an average value of -0.69γ , corresponding to an additional eastward (dusk to dawn) tail field component; its spatial distribution does not show any indication of ordered field lines diverging, even after the tail axis aberration correction. The average of $|B_Y|$ in the plasma sheet is 2.01γ , which is about 50% greater than that observed in the high latitude tail.

The north-south component of the magnetic field (B_Z) has an average value of 1.09γ inside the plasma sheet and its spatial distribution reveals that large B_Z values are detected near the tail equatorial plane and also in the morning side. The magnitude of the field across the neutral sheet is best represented by $|B_Z|$ which has an average value of 1.91γ over the entire plasma sheet, and Figure 13 illustrates its distribution along Y and Z-directions. Longitudinally, the $|B_Z|$ is approximately constant with 1.6γ between $Y_{SM} = 15 R_E$ and $-12 R_E$ and higher near both flanks; latitudinally, it is about constant between $Z_N = \pm 12 R_E$ and slightly enhanced beyond this region.

Angularwise, it is found that the average longitudinal deviation

$|\varphi|$ of field lines from the Sun-Earth direction is 19.65° , which is almost three times larger than that in the high latitude tail lobe. The spatial distribution of $|\varphi|$ has a "w" shaped profile along the Z-direction; it is about 25° at $|Z_N| \geq 15 R_E$ and $\sim 18^\circ$ at $|Z_N| \approx 9 R_E$ with a value of $\sim 20^\circ$ near $Z_N \approx 0 R_E$. Along Y_{SM} axis, it is about 22° near the dusk flank and gradually decreases to $\sim 16^\circ$ near $Y_{SM} \approx -6 R_E$ but then increases to $\sim 25^\circ$ at $Y_{SM} \approx -20 R_E$ (Figure 14).

The observed latitude angle θ inside the plasma sheet is mostly (73.3%) positive with an average value of 10.6° , indicating that the magnetotail neutral point is generally located beyond the lunar orbit. The spatial distribution of θ shows that latitudinally large θ values are generally distributed near the tail equatorial plane ($|Z_N| \leq 6 R_E$) and longitudinally small θ values are in the center of the tail. Figure 15 illustrates the longitudinal and latitudinal variations of $|\theta|$, which indicates the true north-south angular deviation of the field lines, with a value of $\sim 12.5^\circ$ at the tail center ($Y_{SM} \approx -3 R_E$), increasing toward both flanks along Y and approximately with a constant value which is very close to the average of $\sim 19.65^\circ$ along Z axis.

B. Temporal variations

Among the 8791 10-minute magnetic field data obtained in the plasma sheet, 63% of them are observed during periods of low geomagnetic activity ($K_p \leq 1+$) and the rest in active periods ($K_p \geq 2-$). It is found that the spatial distributions of all magnetic field para-

meters, as well as their absolute values, do not change significantly with K_p values. Magnitudewise, however, the field strength B shows the largest variation, increasing from 6.77γ at low K_p to 9.56γ at high K_p (see Figure 11); and consequently $|B_X|$, B_Y , $|B_Y|$, B_Z and $|B_Z|$ are also larger during high K_p than low K_p . The change of the field line configuration (i. e. direction) can be determined from the observations of the angles, θ and φ . The absolute longitude angle $|\varphi|$ does not have a significant change (19.88° at low K_p and 19.27° at high K_p) with geomagnetic activity. However, the average latitude angle θ is 11.64° at low K_p and 8.79° at high K_p ; the average of absolute value of latitudinal angle $|\theta|$ is 17.02° during quiet times and 15.80° during geomagnetically active periods. The occurrence frequency of a positive θ angle decreases slightly from 74.6% at low K_p to 71.2% at high K_p (Figure 16). Thus, the field line configuration variation associated with geomagnetic activity is found only in the latitude angle θ and its absolute value $|\theta|$, namely they are larger during geomagnetically quiet times than active periods.

Seasonally, the field magnitude is about 10% greater in summer than in winter, due to a coincidental uneven K_p distribution; thus, the three field components are also higher in summer than in winter. Angularly, θ , as well as $|\theta|$, are larger (12.73° and 16.16° , respectively) in summer than in winter (8.5° and 15.32°); however, $|\varphi|$ is about the same for two solstice seasons. The ratio of positive to negative θ angles is quite different, from $83.7/16.1$ in summer months to $66.2/33.6$ in winter months.

Table 2 summarizes the magnetic field line characteristics

observed inside the plasma sheet. It is clear that inside the plasma sheet the angular deviation of field lines from the Sun-Earth direction is greater by a factor of three or four than that in the high latitude tail lobes, and the spatial distribution of the magnetic field parameters do not show any indication of a systematic diverging field line structure. The average configuration of field lines does not vary drastically during different geomagnetic activities, but the magnitude of north-south directional deviation, indicated by $|\theta|$, is greater during quiet periods than active periods.

V. Conclusion and discussion

The magnetotail field line configurations near $60 R_E$ are studied extensively in the high latitude tail regime and inside the plasma sheet, by using the magnetic field measurements (34 magnetotail crossings) from the lunar orbiting Explorer 35 satellite.

In the high latitude tail lobes (i. e. outside the plasma sheet), the magnetic field lines are systematically and orderly distributed, with a clear indication of their divergence along the magnetotail. From the distribution of the φ angle, it is found that the field lines gradually diverge longitudinally away from the aberrated tail axis and the diverging angle is about 18° between two flanks with a higher degree of divergence in the dusk side than in the dawn side and in the northern tail than in the southern tail. This 18° longitudinal divergence is in good agreement with the earlier result of Behannon (1970).

The divergence along the latitudinal direction is also observed,

as indicated by negative θ angles. It is located mainly above $Z_N \approx 3 R_E$ and below $Z_N \approx -9 R_E$, but field lines with positive θ angles (corresponding to a convergent configuration) are observed between them. The intrinsic limitation of the lunar orbit confines the Explorer 35 observations to only about $\pm 6 R_E$ in the Z-direction near the midnight meridian, thus, the exact latitudinal divergence at large $|Z|$ values near $Y_{SM} \approx 0$ cannot be determined. Since $|\theta|$ does not depend on Y_{SM} and since $|\theta|$ deviation is about 5° at $|Z_N| \approx 18 R_E$ (together with the fact that $|Y_{SM}|$ values are large), it is estimated that the north-south tail divergence is about 10° .

The fact that the field line divergence angle observed along the Y-direction is about twice as that along the Z-direction reveals that the shape of the tail cross section should be elliptical with the semi-major axis oriented along the solar magnetospheric Y-axis. This result is quite different from the previous report by Behannon (1970) of the semi-major axis along the Z-direction; his result was based on the Explorer 33 magnetopause crossings only at large $-Z$ values.

Inside the plasma sheet, the field lines are angularly deviated along the dusk-to-dawn direction and converging toward the neutral sheet; and the systematic tail divergence does not exist. The longitudinal (east-west) deviation angle $|\varphi|$ is about 20° , corresponding to $|B_Y|$ of about 2γ and the latitudinal (north-south) deviation $|\theta|$ is also very large of about 17° . It is also found that $|B_Z|$ is about 1.9γ without K_p selection and 1.69γ for $K_p \leq 1+$ which are much larger than the $|B_Z|$ reported earlier with a value of $\sim 0.65\gamma$ (Behannon, 1970).

This large increase is due to a clear separation of measurements inside the plasma sheet and those outside of it. This newly observed large $|B_Z|$ indicates that the gradient of the tail field magnitude along the X-direction should be greater than the previously estimated one ($B \propto |X|^{-0.3}$).

The K_p dependence of the field line configuration is not obvious in the high latitude tail lobe, but inside the plasma sheet the latitudinal deviation $|\theta|$ shows a decrease from 17.24° at low K_p to 15.80° at high K_p . Although the standard deviations with respect to these mean values are large (of about 14.4°) due to the fluctuating nature of the field in the plasma sheet, this decrease is still considered meaningful, since it is consistently detected at different Y and Z intervals. It has long been thought that the magnetotail field lines become more dipole-like during the expansion phase of magnetospheric substorms (see for example, McPherron, 1972; Nishida and Nagayama, 1973); thus, the magnetic field line configuration is expected to have a larger latitudinal deviation $|\theta|$ during high K_p than during low K_p . However, the results in this analysis show that in the high latitude tail lobe near $60 R_E$, $|\theta|$ does not change significantly with K_p values; this is in good agreement with an earlier observation in the distant tail region (Meng *et al.*, 1971). Further, inside the plasma sheet, $|\theta|$ is about 1.5° larger at low K_p than at high K_p . This tendency is opposite to what one would expect from the proposed change from a tail-like to a dipole-like field line configuration during substorms, unless this substorm variation is statistically masked by other temporal variations of the magnetotail configuration.

It is also interesting to examine the formation of a new neutral

line (or lines) inside the cislunar distance during substorms, as reported by Nishida and Nagayama (1973) and Nishida and Hones (1974). In Section IV it was shown that the percentage of the occurrence of negative θ angle inside the plasma sheet is 28.6% at high K_p , compared to 25.3% during low K_p . This observed 3.3% increase in the occurrence frequency of negative θ angles seems to be too small to support the speculation that the new neutral line formation inside the lunar orbit is a common feature during substorms. Furthermore, the K_p dependence on the occurrence frequency of negative θ values is practically nil in the center of the plasma sheet (i. e. small $|Z_N|$ and $|Y_{SM}|$) (see Figure 16).

Inside the plasma sheet, the ratio of the number of positive-negative θ angles shows two puzzling features. First of all the occurrence frequency of negative θ angles is 16.1% in summer and becomes doubled (33.6%) in winter. This drastic increase in the winter season could not be explained as due to the seasonal change of the dipole axis orientation and of the plasma sheet location with respect to the lunar orbiting plane, but it may be attributed to the differences in the lunar orbiting distances across the tail during these two solstice seasons. In summer, the lunar orbit is at about $X = -57 R_E$ in the tail, but it is further downstream in the tail at $X \approx -63 R_E$ (i. e. closer to the average location of the neutral line) in winter. The other puzzling observation is the very low occurrence frequency of negative θ angles located in the region $-18 R_E \leq Y_{SM} \leq -6 R_E$, shown in Figure 16. At this Y_{SM} interval, very high energetic electron fluxes have been observed by Vela at $X \approx -18 R_E$ and by Explorer 35 satellites at lunar orbit (Montgomery, 1968; Meng, 1971). However, whether this low

occurrence frequency of negative θ values has any relationship with the large energetic electron fluxes requires further study.

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Table 1 Field line components observed in the high latitude tail lobe

Parameter	Magnitude						Distribution ⁵
	Average	$K_p \leq 1^+$	$K_p \geq 2^-$	Equinox	Summer ²	Winter ³	
B	10.8 γ	9.4 γ	13.2 γ	10.2 γ	12.5 γ ¹	10.4 γ	Greater for small $ Y $ Greater in the southern tail ¹
B_X	0.15 γ	0.75 γ	-3.57 γ	-1.4 γ	-11.6 γ ²	9.5 γ ³	Greater for small $ Y $ + B_X in +Z; - B_X in -Z region
$ B_X $	10.6 γ	9.3 γ	13.0 γ	10.0 γ	12.4 γ ¹	10.2 γ	same as B
B_Y	-0.30 γ	-0.44 γ	-0.06 γ	-0.24 γ	+0.59 γ	-1.19 γ	- B_Y in (+Y, +Z) and (-Y, -Z) regions ⁴ + B_Y in (-Y, +Z) and (+Y, -Z) regions ⁴
$ B_Y $	1.3 γ	1.2 γ	1.5 γ	1.2 γ	1.4 γ	1.4 γ	Greater near dusk flank, decreasing toward $Y \approx 0$, constant in -Y; greater at large $ Z_N $
B_Z	0.15 γ	0.06 γ	0.3 γ	0.1 γ	0.4 γ	-0.02 γ	$B_Z < 0$ at +Y, $B_Z > 0$ at -Y $B_Z < 0$ at large $ Z_N $, $B_Z > 0$ at $-10 \leq Z_N \leq 5 R_E$
$ B_Z $	0.8 γ	0.7 γ	1.0 γ	0.8 γ	0.9 γ	0.7 γ	uniform over Y's and Z's.
φ	no meaning				181 $^\circ$ ²		$< 180^\circ$ in (+Y, -Z) region, $> 180^\circ$ in (-Y, -Z) $> 0^\circ$ in (-Y, +Z) region, $< 360^\circ$ in (+Y, +Z)
$ \varphi $	7.1 $^\circ$	7.3 $^\circ$	6.6 $^\circ$	7.0 $^\circ$	6.3 $^\circ$	7.9 $^\circ$	Greater near dusk flank, decreasing toward $Y \approx 0$, constant in -Y. - Greater at large $ Z_N $, smaller at $Z_N \approx -5 R_E$
θ	0.7 $^\circ$ + θ 55% - θ 44%	0.4 $^\circ$ + θ 53% - θ 46%	1.2 $^\circ$ + θ 59% - θ 40%	0.5 $^\circ$ + θ 54% - θ 45%	2.1 $^\circ$ + θ 67% - θ 32%	-0.2 $^\circ$ + θ 47% - θ 52%	Negative in +Y, positive in -Y, Negative at large $ Z_N $, positive at $-12 \leq Z_N \leq +6 R_E$
$ \theta $	4.29 $^\circ$	4.31 $^\circ$	4.25 $^\circ$	4.5 $^\circ$	4.1 $^\circ$	4.1 $^\circ$	Approximately uniform over Y's and Z's.

Notes: ¹Likely due to K_p effect, not true spatial or seasonal variation²Observations limited in the southern tail³Winter observations limited in the northern tail⁴After magnetotail axis aberration correction⁵No change with K_p and season

Table 2 Field line components observed inside the plasma sheet

Parameter	Magnitude						Distribution ⁵
	Average	$K_p \leq 1^+$	$K_p \geq 2^-$	Equinox	Summer ²	Winter ³	
B	7.81 γ	6.77 γ	9.56 γ	7.39 γ	8.19 γ^1	8.08 γ	approximately uniform
B_X	0.04 γ	0.59 γ	-0.89 γ	-0.35 γ	-5.62 γ^2	4.43 γ^3	+ B_X in the +Z region - B_X in the -Z region
$ B_X $	6.73 γ	5.83 γ	8.25 γ	6.25 γ	7.82 γ^1	7.13 γ	approximately uniform
B_Y	-0.69 γ	-0.70 γ	-0.68 γ	-0.56 γ	-0.45 γ	-1.12 γ	- B_Y over the whole cross section
$ B_Y $	2.01 γ	1.79 γ	2.38 γ	1.94 γ	2.23 γ	2.02 γ	larger at high Z ($ Z \geq 12 R_E$) larger near both flanks
B_Z	1.09 γ	1.07 γ	1.13 γ	1.15 γ	1.54 γ	0.69 γ	larger near the $Z_N \approx 0$ plane larger in the dusk side of the tail
$ B_Z $	1.91 γ	1.69 γ	2.28 γ	1.94 γ	2.08 γ	1.75 γ	larger in the morning side about constant between $Z_N \approx \pm 12 R_E$ slightly higher beyond $ Z_N \leq 12 R_E$
φ	no meaning				188.9 $^\circ$		
$ \varphi $	19.7 $^\circ$	19.88 $^\circ$	19.27 $^\circ$	20.70 $^\circ$	18.20 $^\circ$	18.26 $^\circ$	larger near both flanks larger at high Z ($ Z \geq 12 R_E$)
θ	10.57 $^\circ$ + θ 73.3% - θ 26.5%	11.64 $^\circ$ + θ 74.6% - θ 25.3%	8.79 $^\circ$ + θ 71.2% - θ 28.6%	10.91 $^\circ$ + θ 73.6% - θ 26.3%	12.73 $^\circ$ + θ 83.7% - θ 16.1%	8.50 $^\circ$ + θ 66.2% - θ 33.6%	larger near the equatorial plane ($ Z_N \leq 6 R_E$) larger near both flanks
$ \theta $	16.56 $^\circ$	17.02 $^\circ$	15.80 $^\circ$	17.24 $^\circ$	16.16 $^\circ$	15.32 $^\circ$	approximately constant along Z_N larger near both flanks

Notes: see Table 1

Figure Captions

- Figure 1. Spatial distribution of 10-min average magnetic field data. The upper and lower values in each $3 R_E \times 3 R_E$ square are the number of field measurements obtained in the high latitude tail lobe (i. e. outside the plasma sheet) and inside the plasma sheet, respectively.
- Figure 2. Distribution of the magnetic field magnitude observed in the high latitude tail during different geomagnetic activities. The arrow indicates the average value.
- Figure 3. Longitudinal and latitudinal distributions of the high latitude field magnitude.
- Figure 4. Spatial distribution of the high latitude field X-component. The upper value is the average of the B_X in that areal element and the lower value is the average of the $|B_X|$.
- Figure 5. Spatial distribution of the high latitude field Y-component. Lower values are the averages of the observed B_Y . Upper values include the magnetotail axis aberration correction of $\pm 0.6\gamma$ in $\pm Z$; thus, they represent a distribution of B_Y with respect to the aberrated magnetotail axis.
- Figure 6. Longitudinal and latitudinal distributions of azimuthal deviation of the high latitude tail field lines with respect to the sun-earth alignment. $|\varphi|$ refers to the absolute angular deviation of φ from 0° or 180° axis. Please note that a gradually increasing $|\varphi|$ in the dusk side (+Y's) represents a "fan shaped" field line divergence away from the center of the tail.

Figure 7. Longitudinal and latitudinal distributions of the latitude angle (θ) and B_Z -component. A positive and negative θ (or B_Z) represents the north-south convergence and divergence, respectively, of the field lines with respect to the solar magnetospheric equatorial plane (or the neutral sheet).

Figure 8. Distribution of the occurrence frequency for negative θ angles (i. e. latitudinal diverging field lines).

Figure 9. The longitudinal distribution of the absolute azimuthal angular deviations away from the sun-earth line observed in the high latitude tail during summer and winter months. The deviation in the dusk side is larger in winter than in summer. This is owing to the asymmetric field line divergence in the northern and southern tail, since the summer and winter observations were limited in the southern and northern magnetotail, respectively.

Figure 10. The longitudinal distribution of the high latitude field line azimuthal angle (φ) observed in the summer months (i. e. only in the southern tail). The fan shaped longitudinal divergence of field lines away from the center of the tail is rather obvious and it is clear that the rate of divergence is greater in the dusk side than in the dawn side of the tail.

Figure 11. Distributions of the magnetic field magnitude, B_Y and B_Z with respect to their averaged values, observed inside the plasma sheet. The scatter of B is larger inside the plasma sheet than in the high latitude tail as shown in Figure 2.

Figure 12. Spatial distributions of the plasma sheet magnetic field component B_X and $|B_X|$. Longitudinal and latitudinal distributions of $|B_X|$ are also shown on the top and right hand side of the spatial distribution.

Figure 13. Longitudinal and latitudinal distributions of the plasma sheet field intensity across the neutral sheet ($|B_z|$) during different geomagnetic conditions.

Figure 14. Similar to Figure 13, but for the absolute azimuthal angular deviations from sun-earth alignment observed inside the plasma sheet.

Figure 15. Similar to Figure 13, but for the absolute latitudinal (north-south) angular deviation from the solar magnetospheric equatorial plane observed inside the plasma sheet.

Figure 16. Similar to Figure 13, but for the occurrence frequency of negative θ angles inside the plasma sheet.

DISTRIBUTIONS OF MAGNETIC OBSERVATION

Upper No. : High Latitude Lobe Lower No. : Plasma Sheet

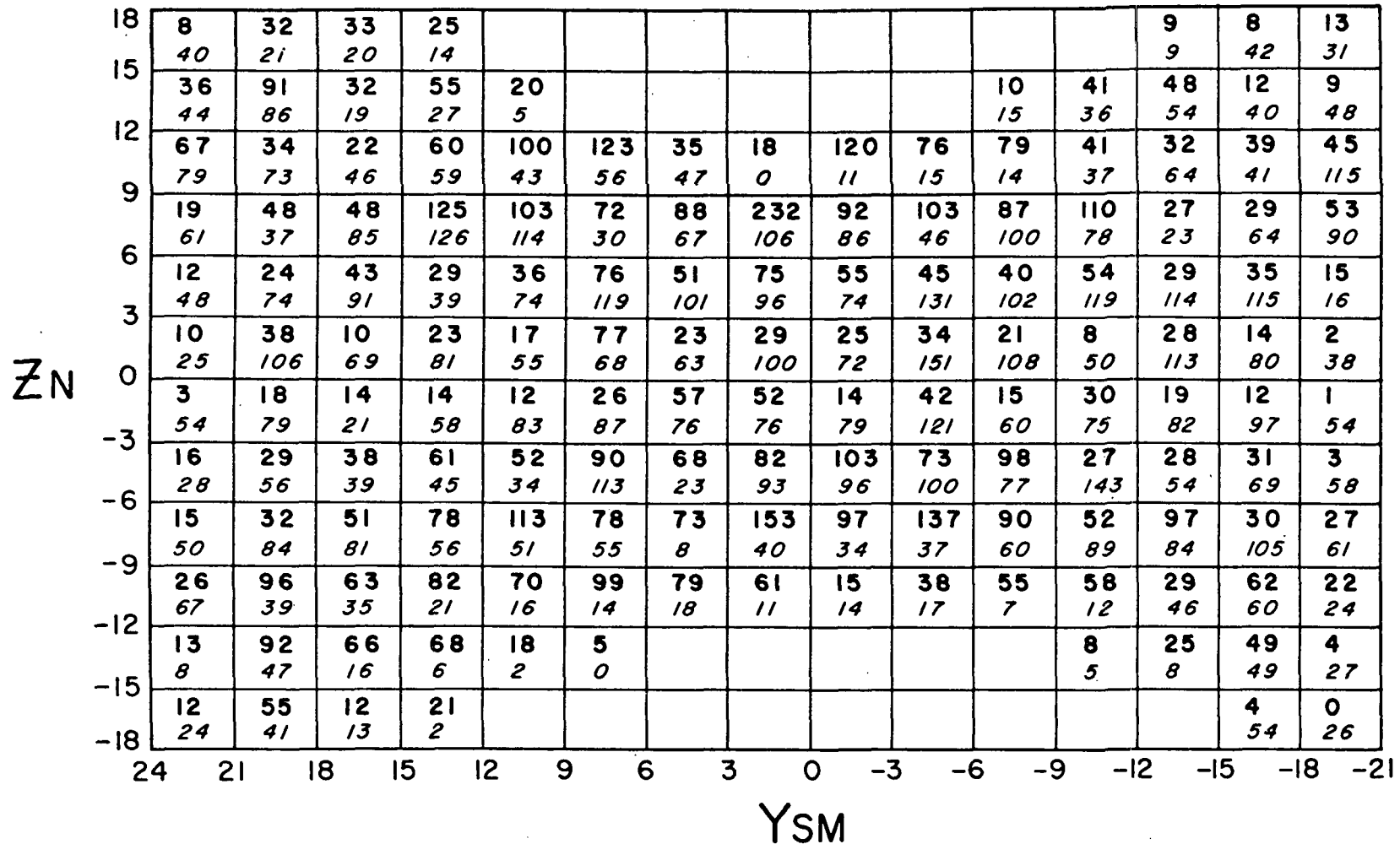


Figure 1

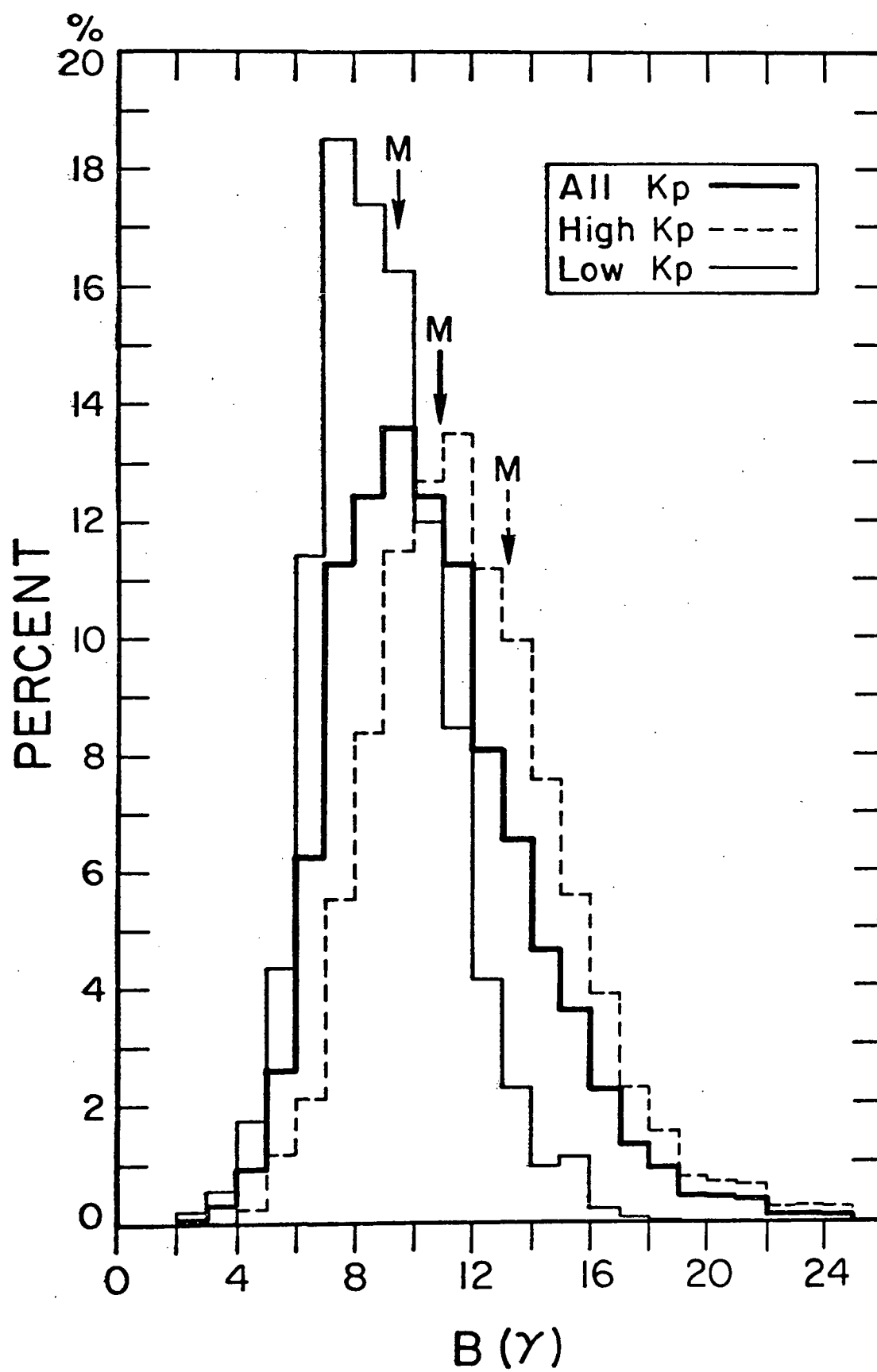


Figure 2

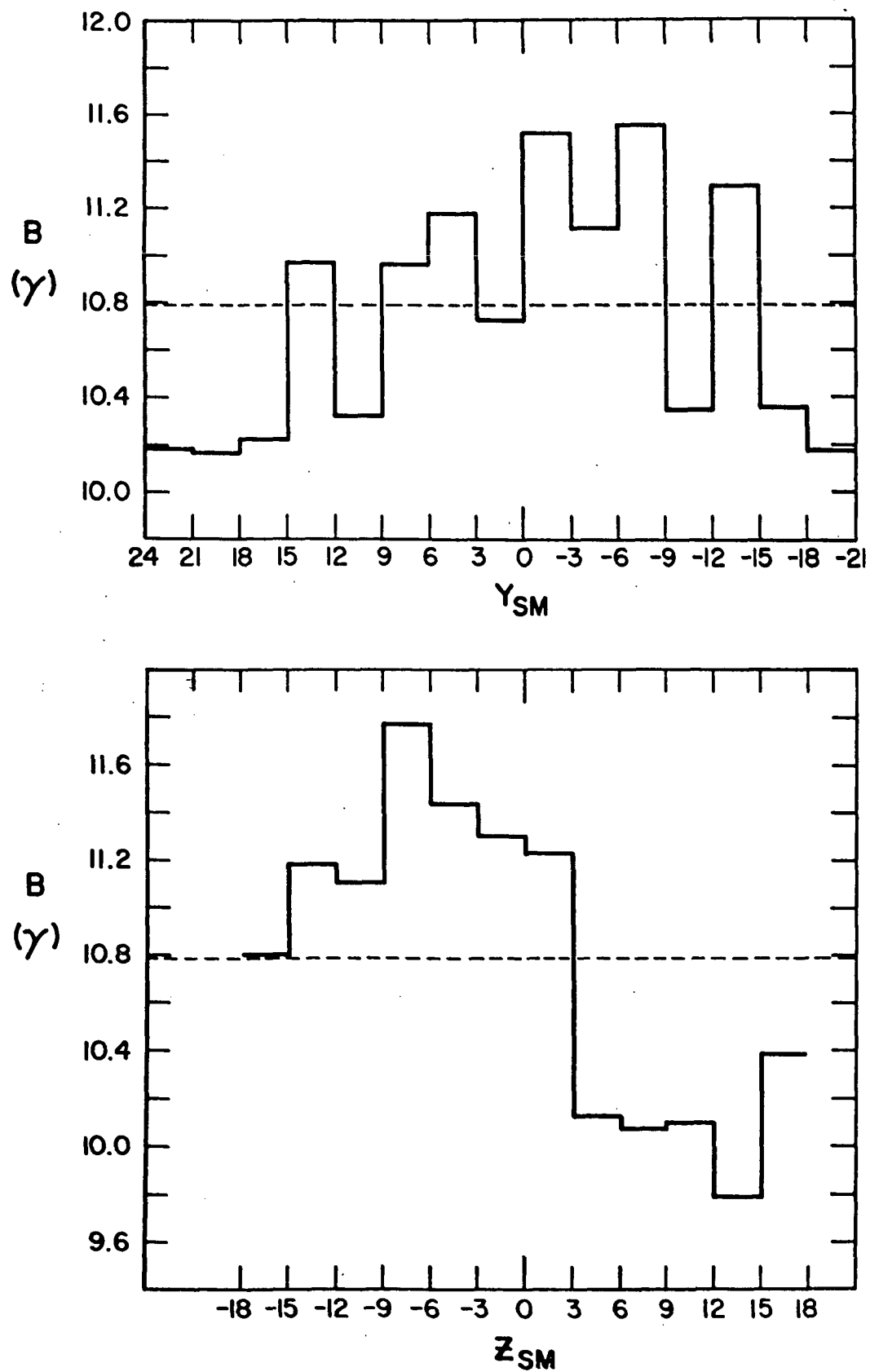


Figure 3

DISTRIBUTIONS OF HIGH LATITUDE LOBE B_x , $|B_x|$

Upper No.: B_x

Lower No.: $|B_x|$

Z _N	18	10.08	10.93	9.82	9.65									11.25	8.09	9.98	
	15	8.92	8.99	11.37	9.36	11.00						12.43	6.68	10.26	12.00	9.81	
	12	8.93	8.01	8.98	11.46	8.68	10.55	7.34	8.48	12.19	10.80	10.31	7.79	7.32	11.44	9.11	
	9	9.24	9.27	8.91	10.90	10.23	12.10	10.58	9.34	8.84	9.30	10.39	9.50	9.76	9.65	9.82	
	6	13.46	15.55	11.51	5.09	7.94	7.95	9.94	7.01	8.89	4.51	6.23	10.06	9.88	8.58	12.70	
	3	10.29	8.46	10.69	8.52	7.15	-0.15	-1.04	4.98	3.22	3.74	7.85	9.57	-4.76	9.07	-14.30	
	0	9.37	-0.68	-12.28	-4.53	-7.15	-11.14	-10.84	-5.76	-5.79	-5.49	-6.14	-5.34	-7.60	-10.56	-3.89	
	-3	-11.06	-10.21	-7.29	-11.08	-11.53	-10.86	-11.14	-11.04	-11.71	-11.95	-12.86	-10.82	-12.17	-11.46	-12.97	
	-6	-10.33	-7.78	-8.94	-9.71	-9.50	-11.25	-13.32	-13.25	-14.27	-12.46	-12.42	-11.19	-11.82	-10.01	-10.01	
	-9	-8.92	-9.97	-9.85	-11.42	-10.98	-10.53	-10.66	-10.34	-11.08	-15.10	-11.96	-13.83	-11.85	-9.20	-10.93	
	-12	-12.80	-9.75	-9.90	-11.82	-11.65	-10.79						-11.53	-14.17	-11.24	-13.66	
	-15	-8.38	-10.29	-12.06	-11.78										-10.22		
	-18																
		24	21	18	15	12	9	6	3	0	-3	-6	-9	-12	-15	-18	-21
		Y _{SM}															

Figure 4

DISTRIBUTION OF HIGH LATITUDE LOBE B_Y

Upper No.: Corrected B_Y (γ) Lower No.: Observed B_Y (γ)

Z _N	18	-1.29	-1.87	-1.46	-1.99									-0.34	1.49	0.49	
	15	-1.60	-1.32	-1.91	-1.31	-2.60						1.11	0.05	0.24	0.77	1.39	
	12	-1.56	-0.87	-1.52	-1.95	-1.21	-1.08	-0.02	0.12	-0.04	0.01	0.08	0.31	0.13	-0.71	0.47	
	9	-1.95	-1.28	-0.96	-1.91	-1.35	-1.46	-0.84	-0.48	-0.21	0.07	-0.25	0.14	0.14	0.74	0.46	
	6	-3.28	-2.90	-2.20	-0.68	-1.11	-0.72	-0.78	0.42	0.73	0.26	0.22	-0.02	0.33	0.49	0.72	
	3	-1.35	-1.05	-1.99	-1.08	0.35	0.09	0.91	-0.53	0.33	0.19	-0.04	-0.15	0.26	0.78	0.21	
	0	-2.10	-0.52	2.45	0.17	0.52	0.55	0.31	-0.08	-0.09	-0.76	-0.85	-1.57	-1.27	-0.53	-0.63	
	-3	1.65	1.18	0.50	1.43	0.73	0.37	-0.53	-0.03	-0.17	-0.23	-0.23	-1.18	-1.37	-0.92	-2.60	
	-6	1.02	0.49	1.20	0.71	0.26	0.28	0.18	0.36	-0.25	-0.61	-0.74	-1.12	-0.89	-1.27	-1.25	
	-9	0.81	1.40	-0.06	0.50	0.35	0.38	-0.10	-0.42	-1.66	-0.38	-0.92	-1.40	-0.87	-1.14	-1.00	
	-12	0.47	0.79	0.73	1.17	0.68	0.73						-1.39	-1.53	-1.33	-1.77	
	-15	0.30	1.05	1.20	1.48										-0.87		
	-18	0.90	1.65	1.80	2.08										-0.27		
		24	21	18	15	12	9	6	3	0	-3	-6	-9	-12	-15	-18	-21
		Y _{SM}															

Figure 5

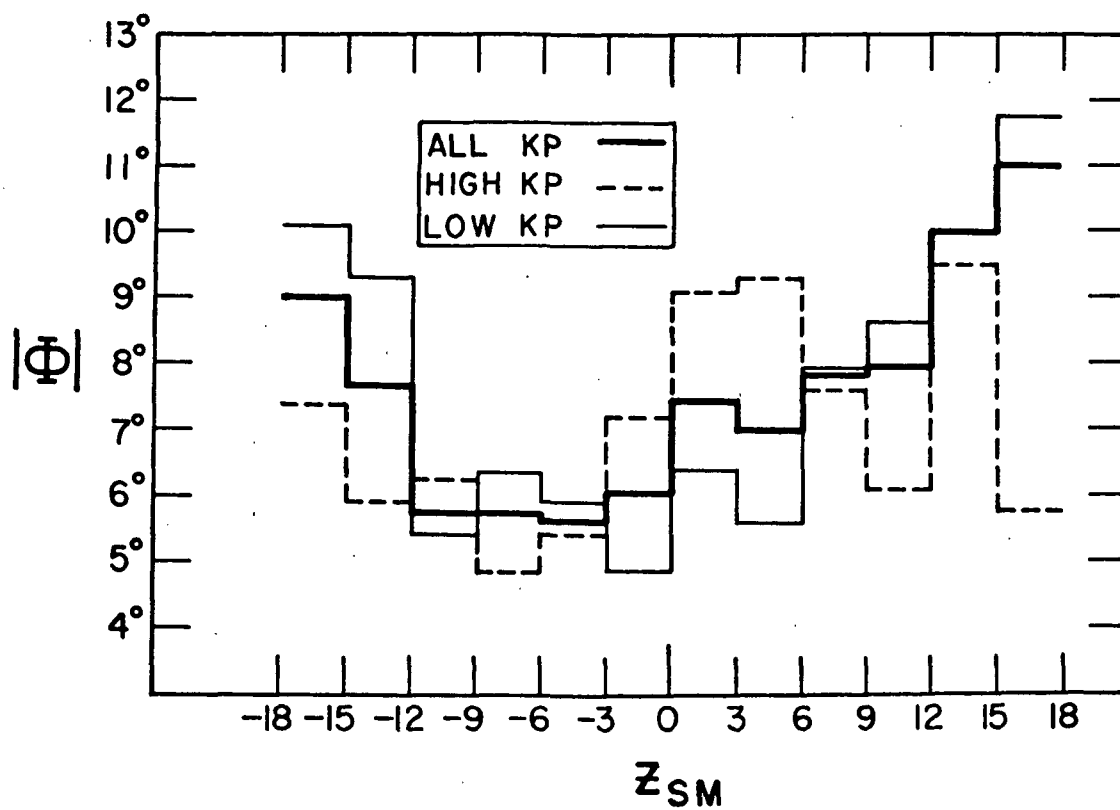
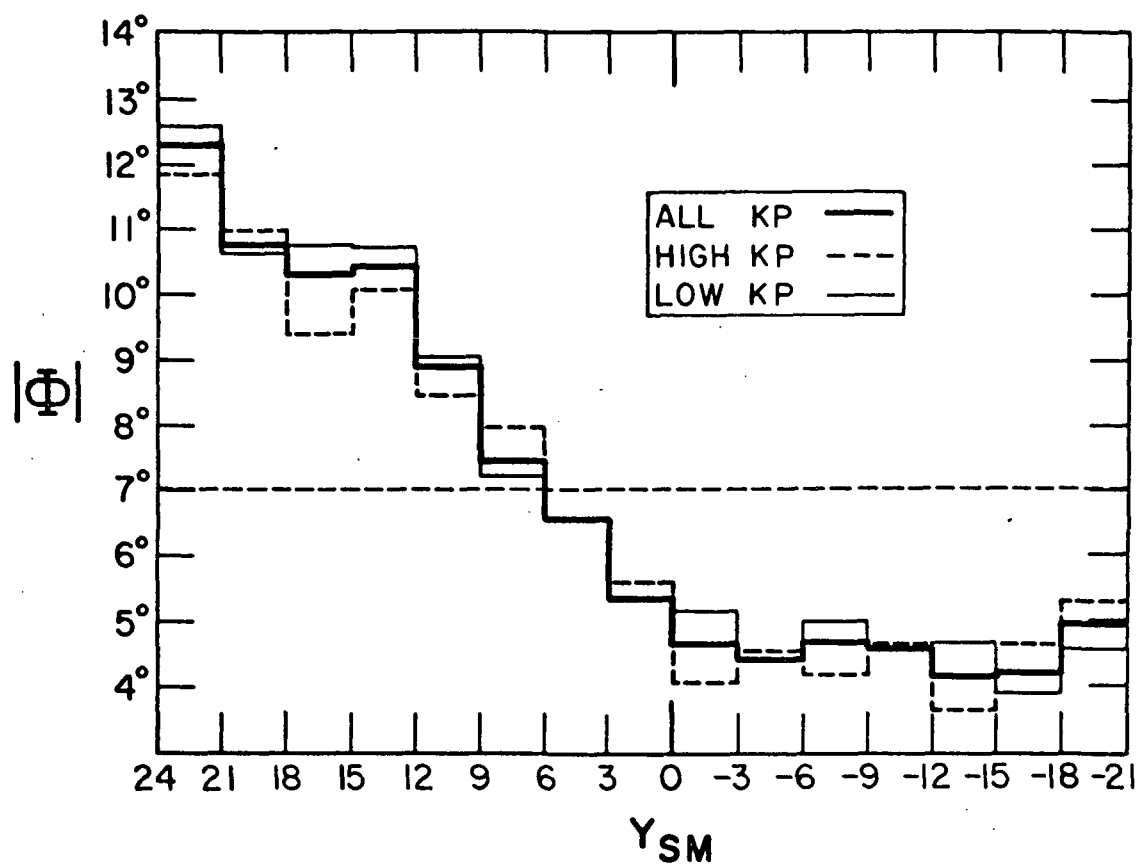


Figure 6

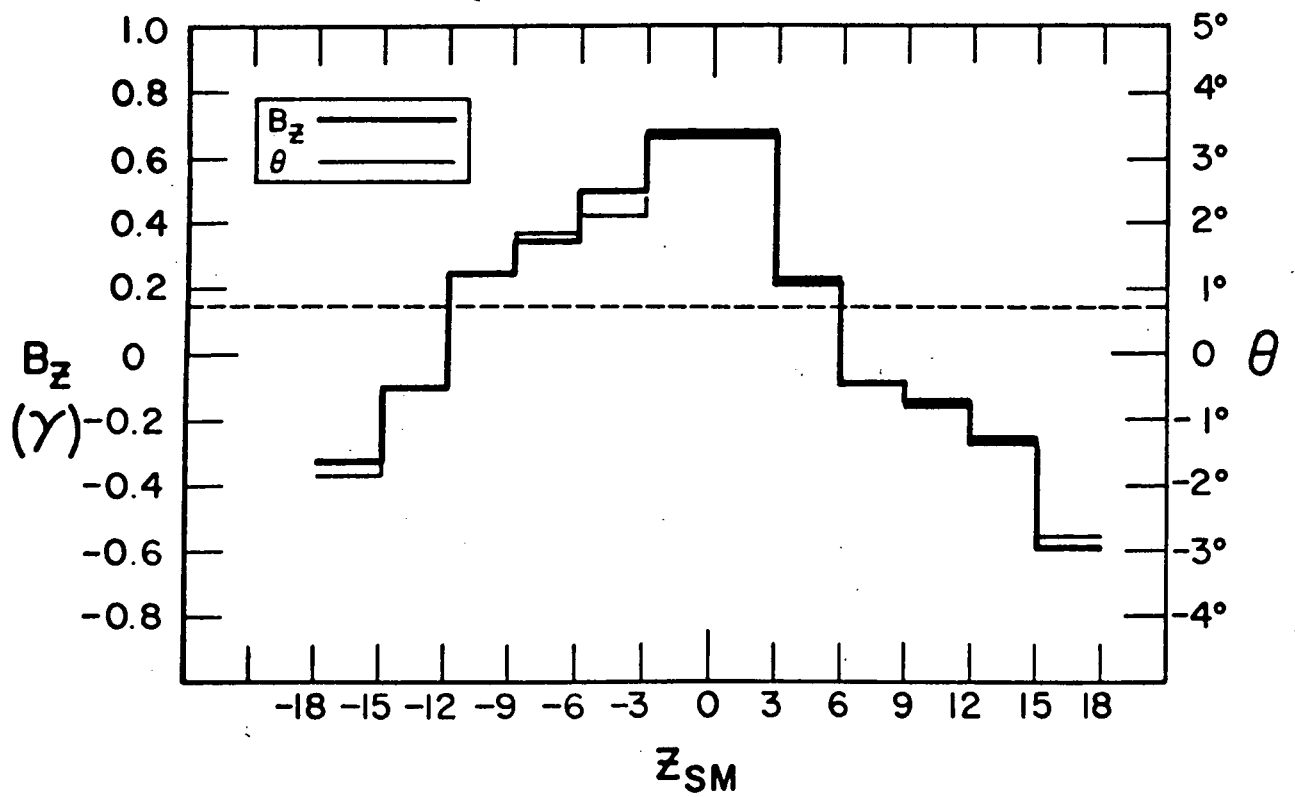
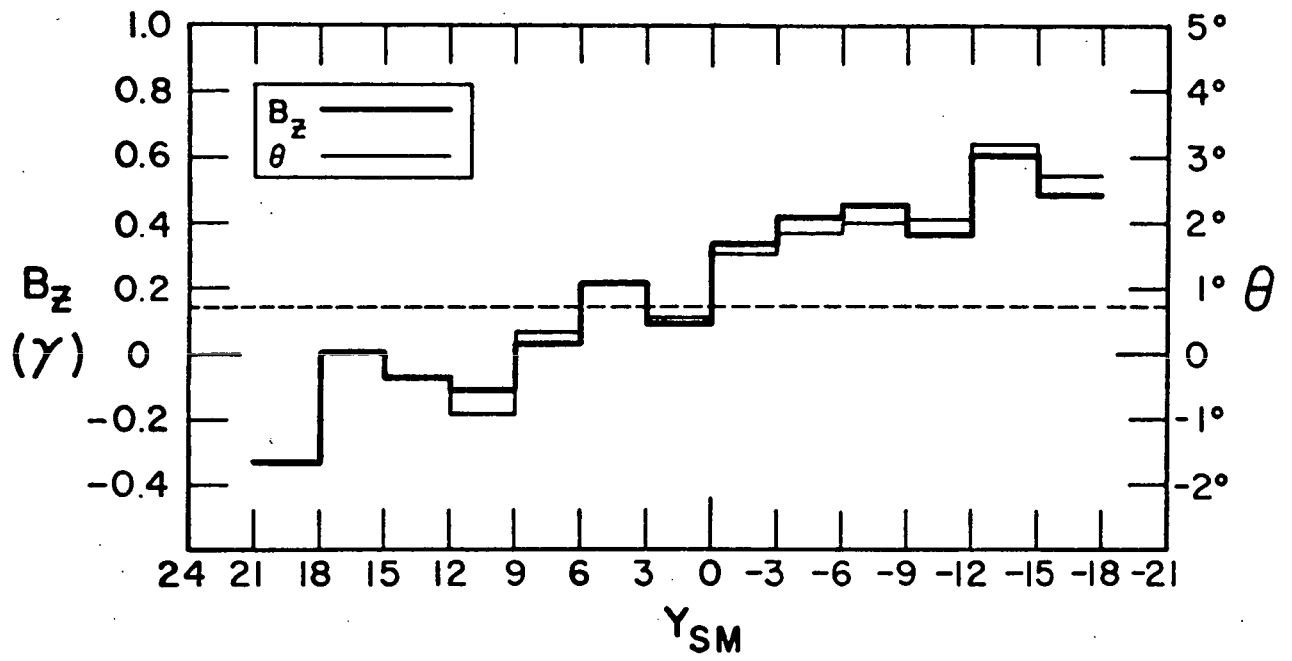


Figure 7

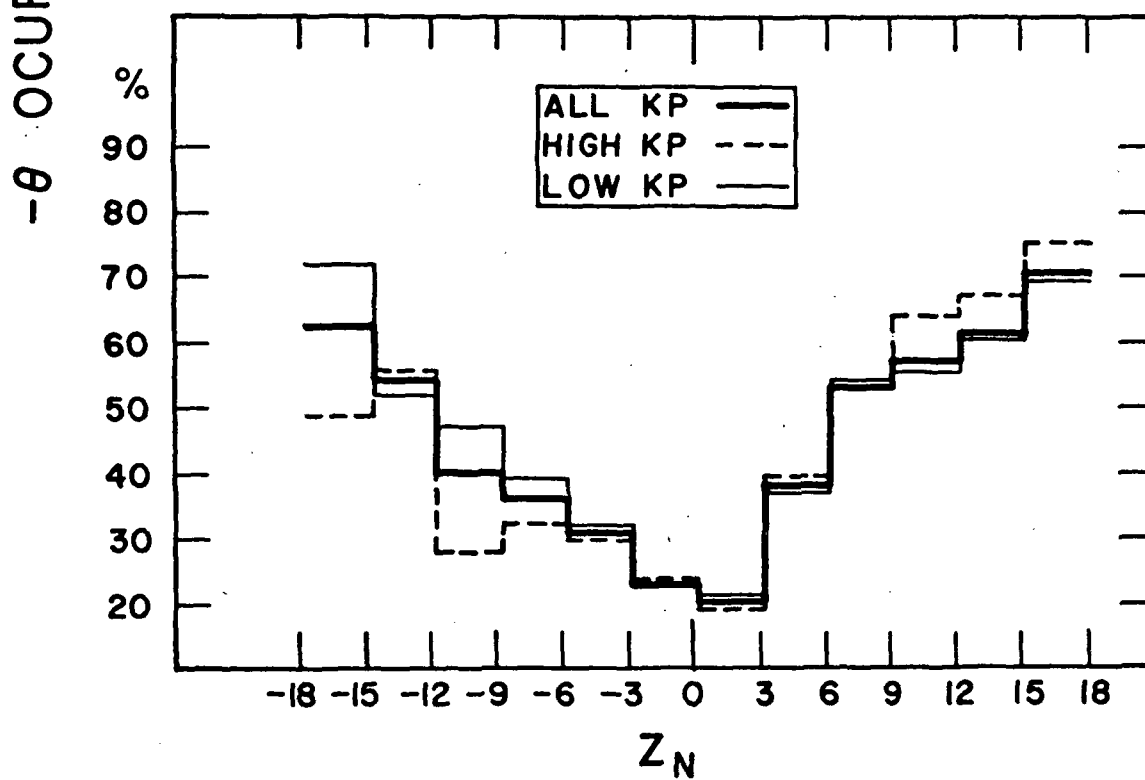
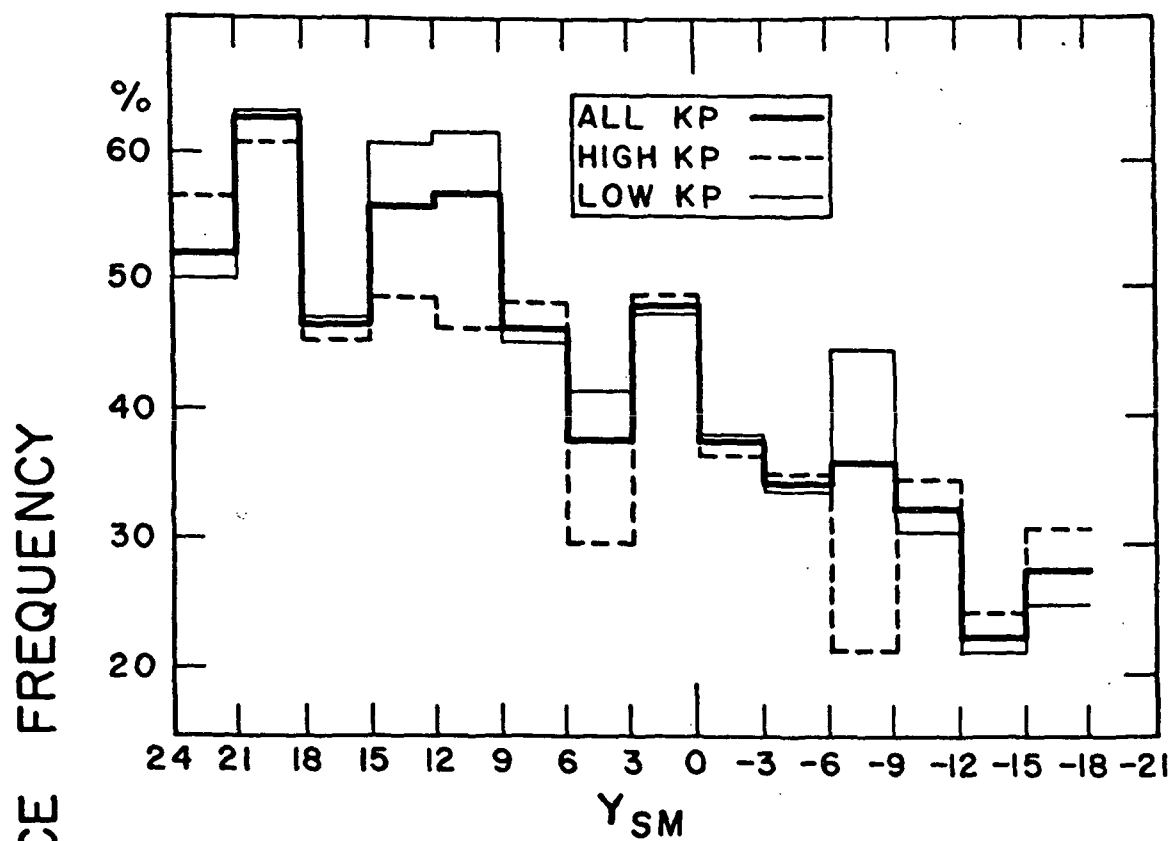


Figure 8

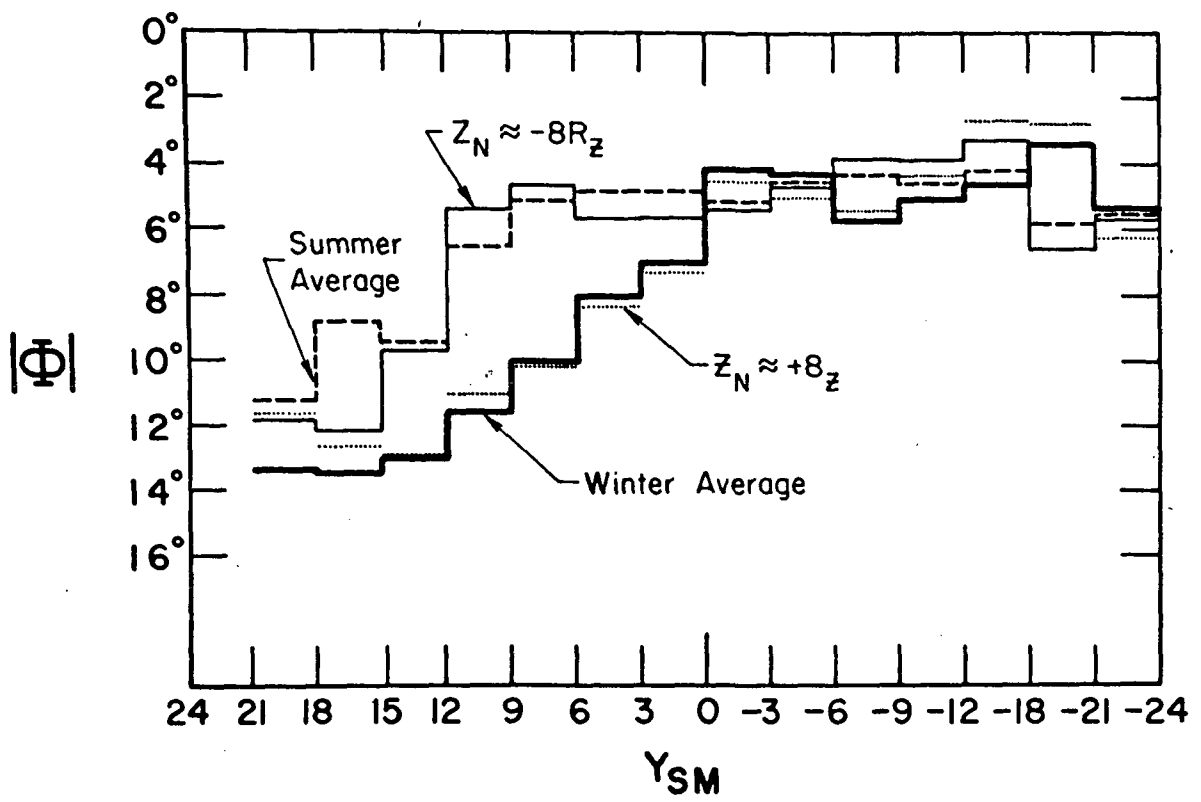


Figure 9

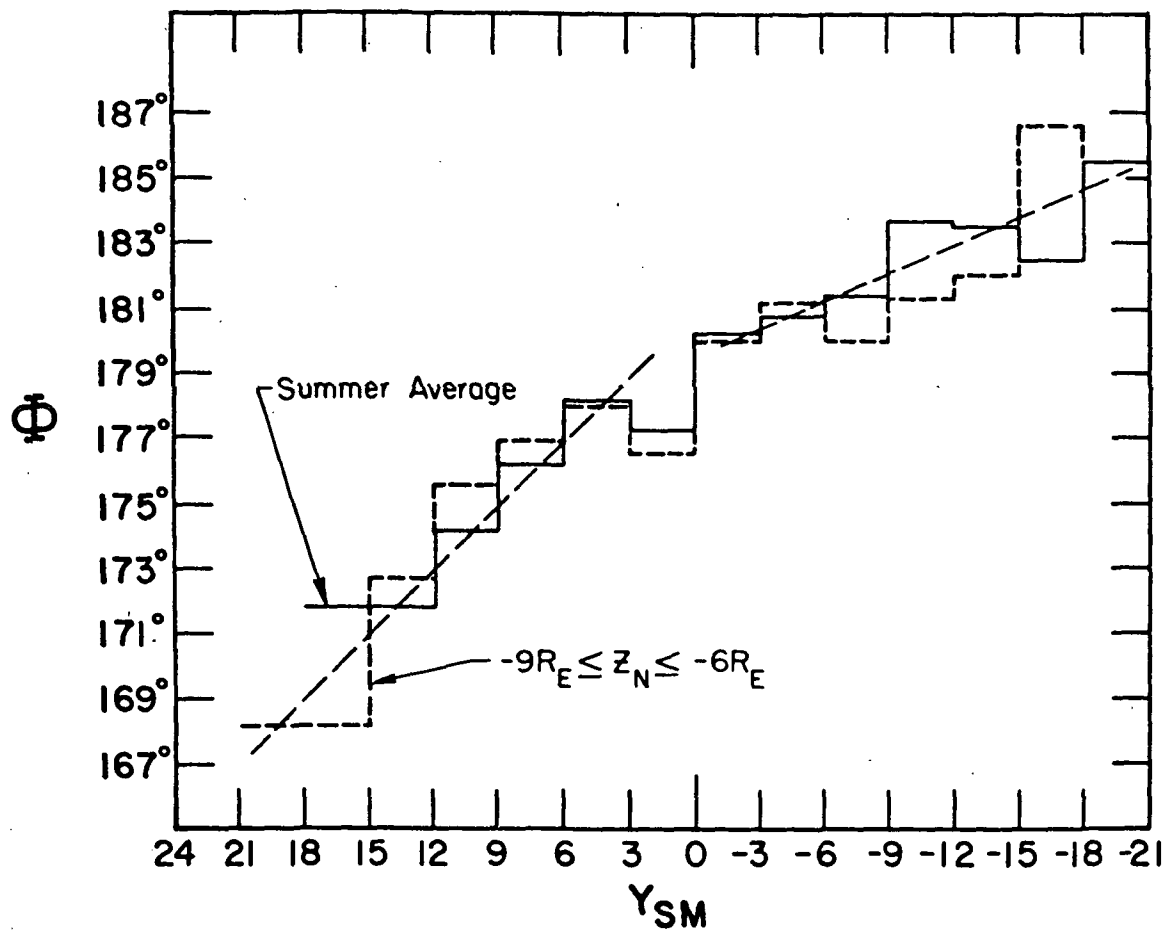


Figure 10

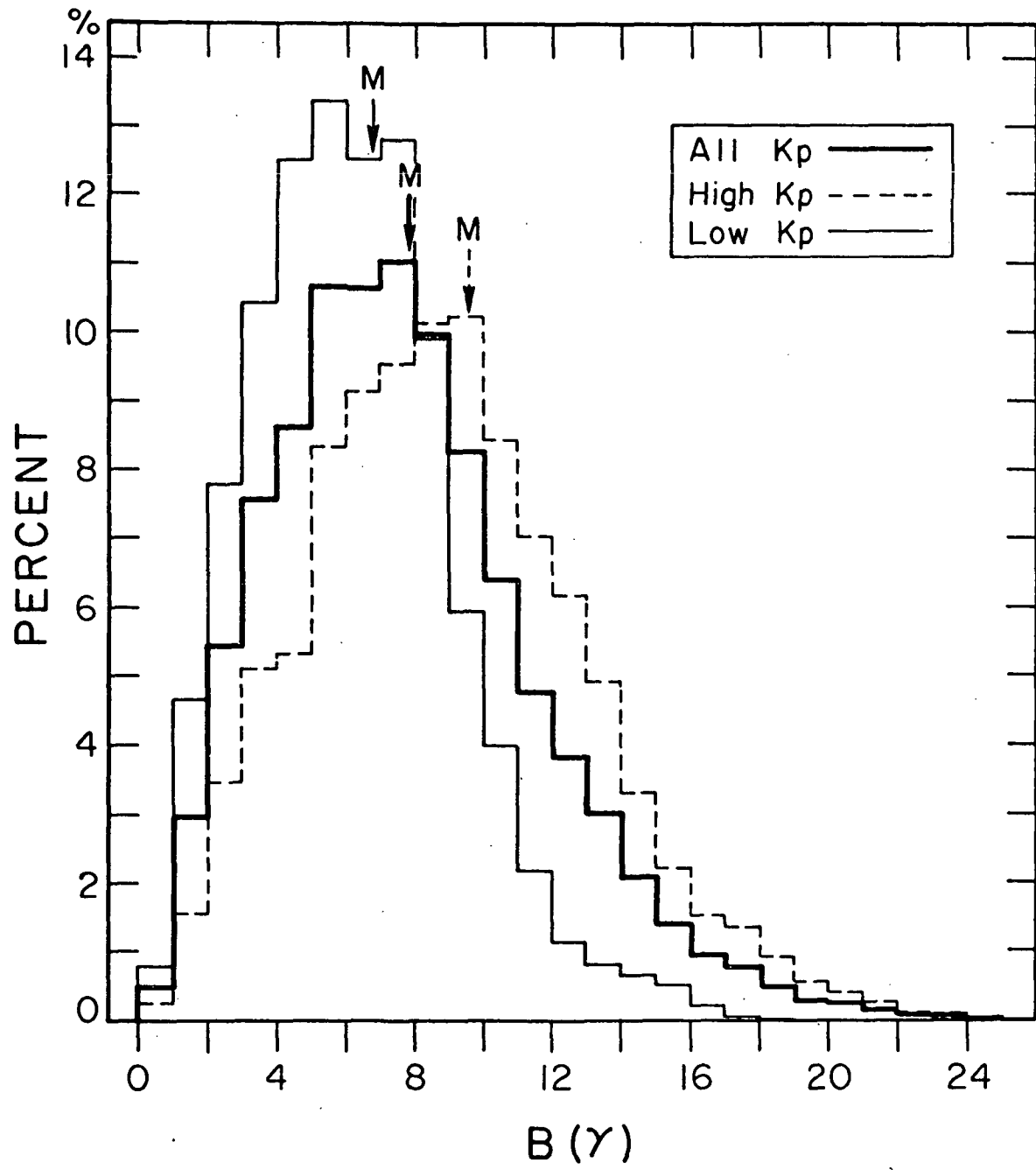


Figure 11

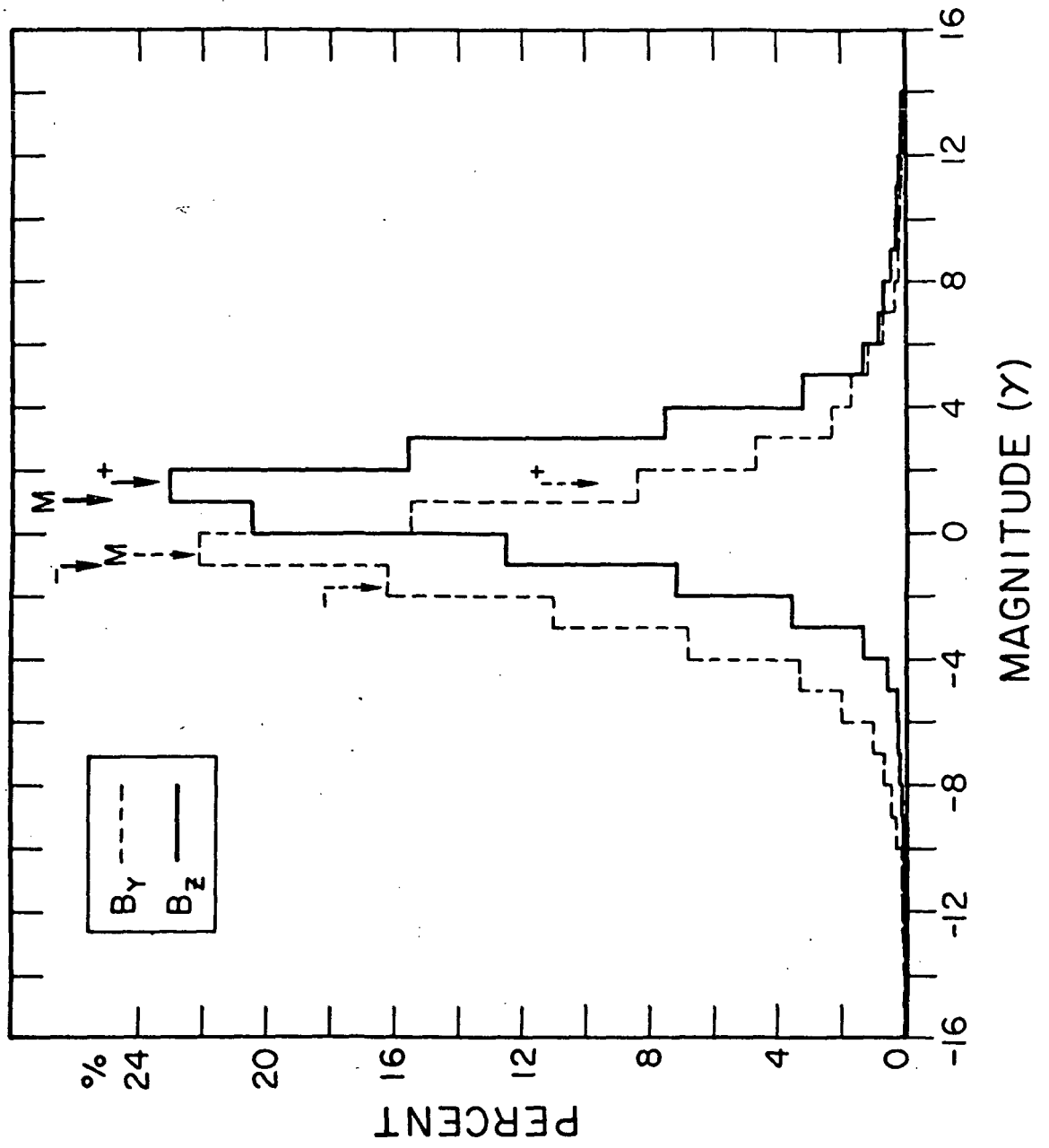


Figure 11
(cont.)

DISTRIBUTIONS OF PLASMA SHEET B_x , $|B_x|$

Upper No.: B_x

Lower No.: $|B_x|$

6.30	6.70	6.51	7.31	7.07	6.89	7.73	7.01	7.58	6.89	7.12	6.31	6.71	6.16	5.69
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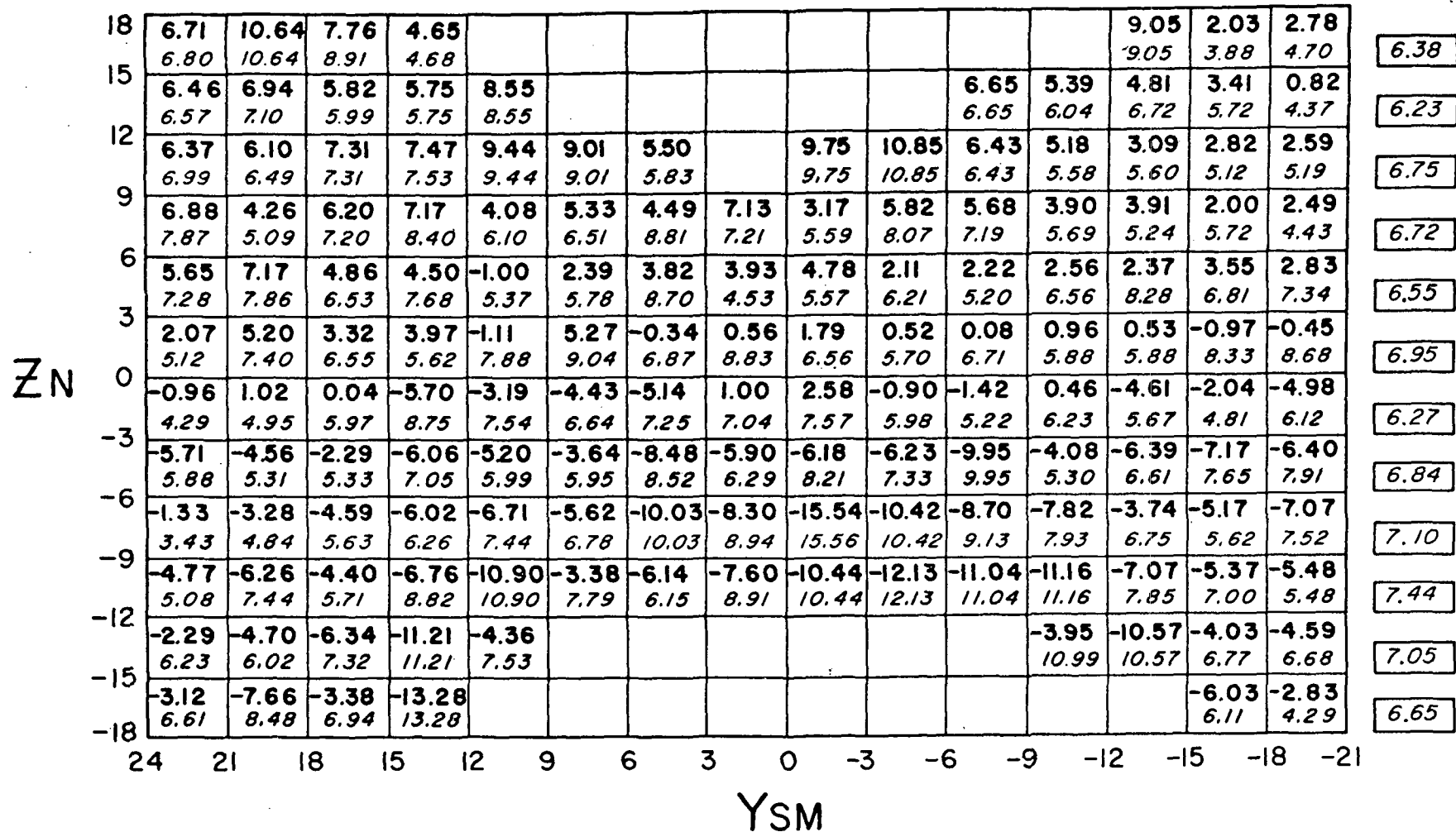


Figure 12

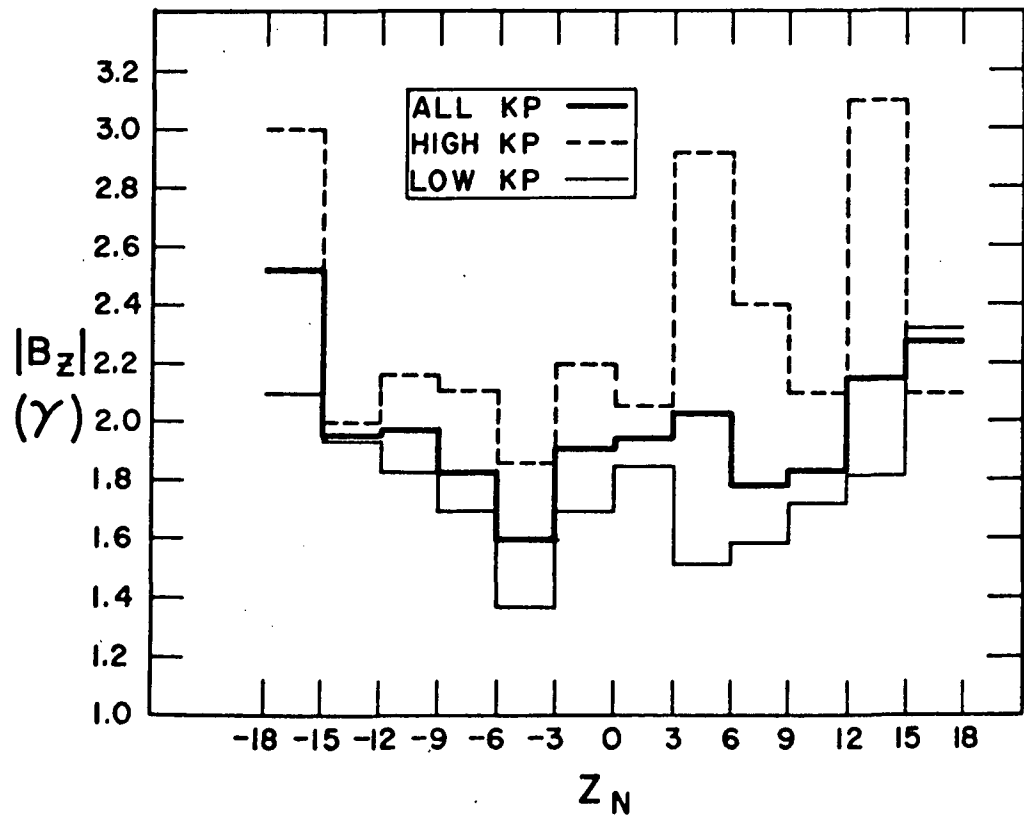
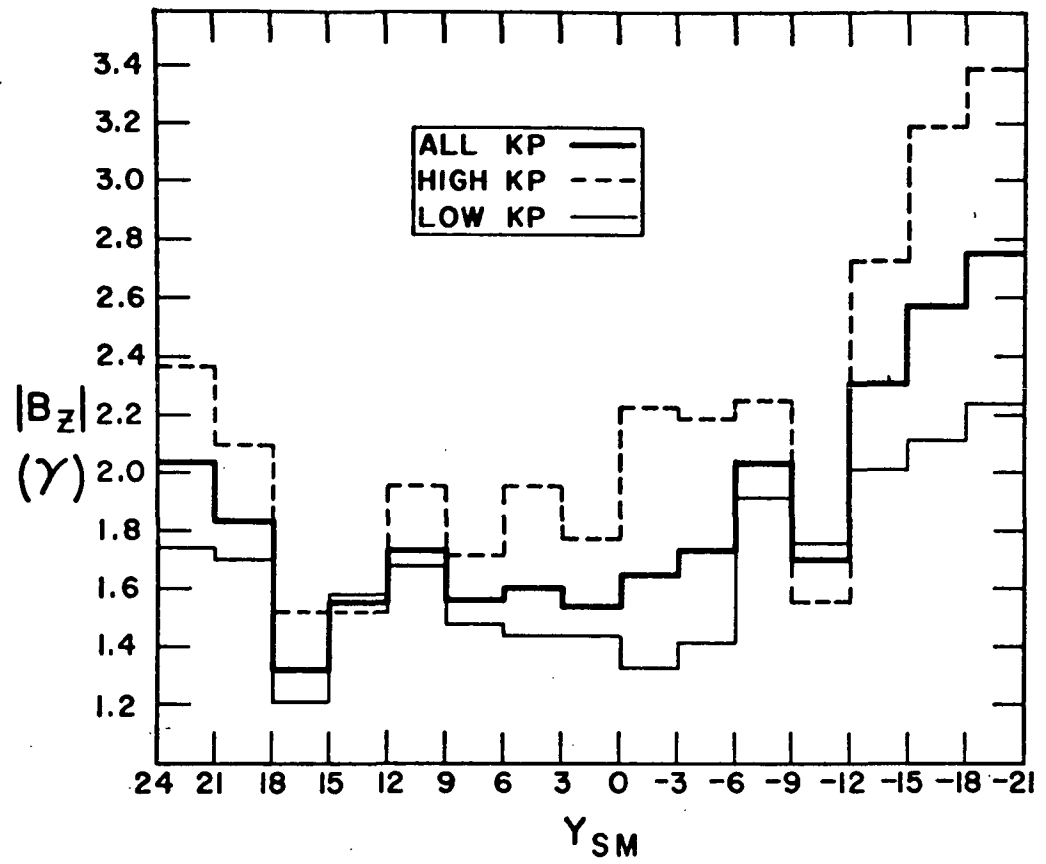


Figure 13

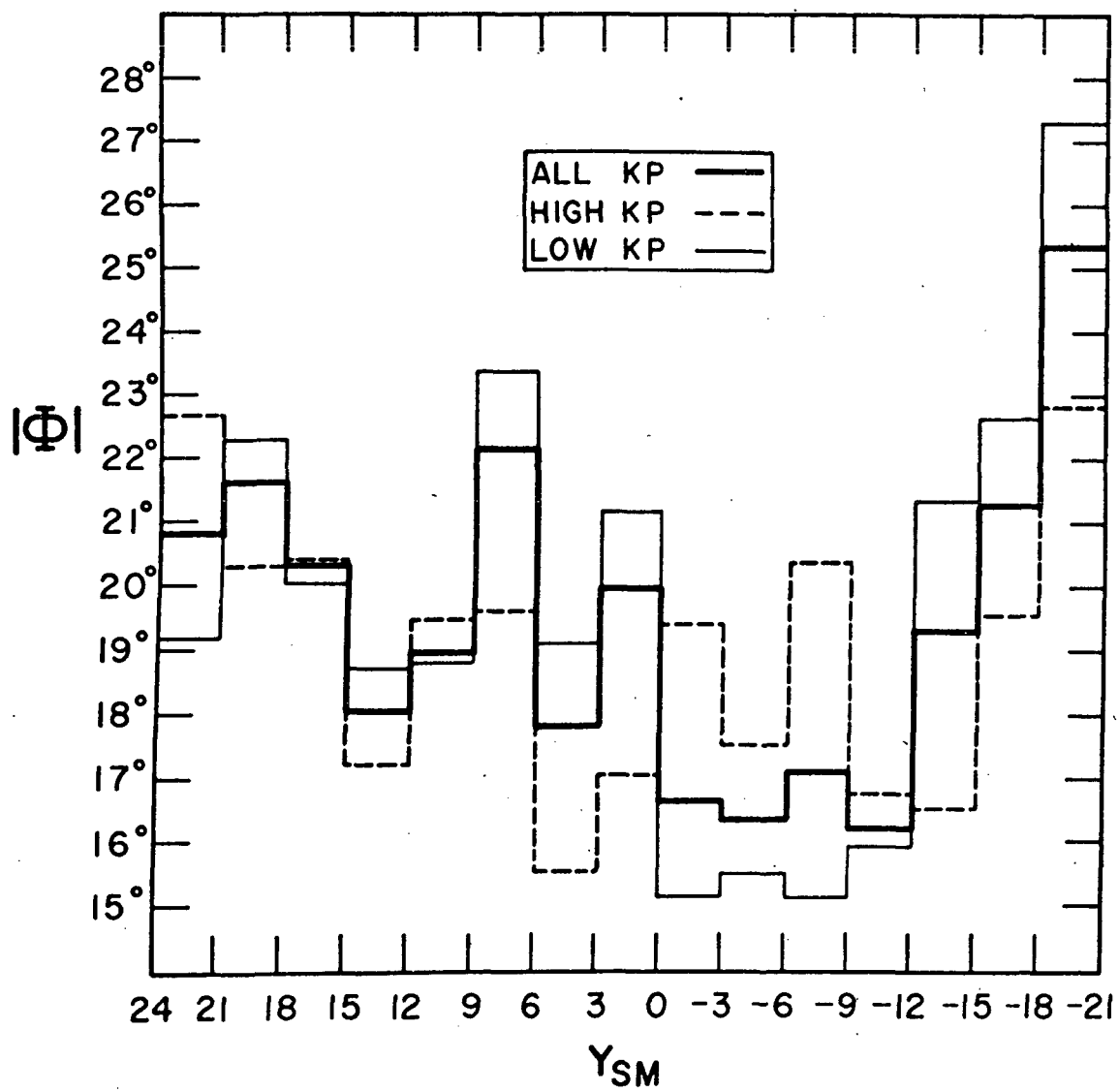


Figure 14.

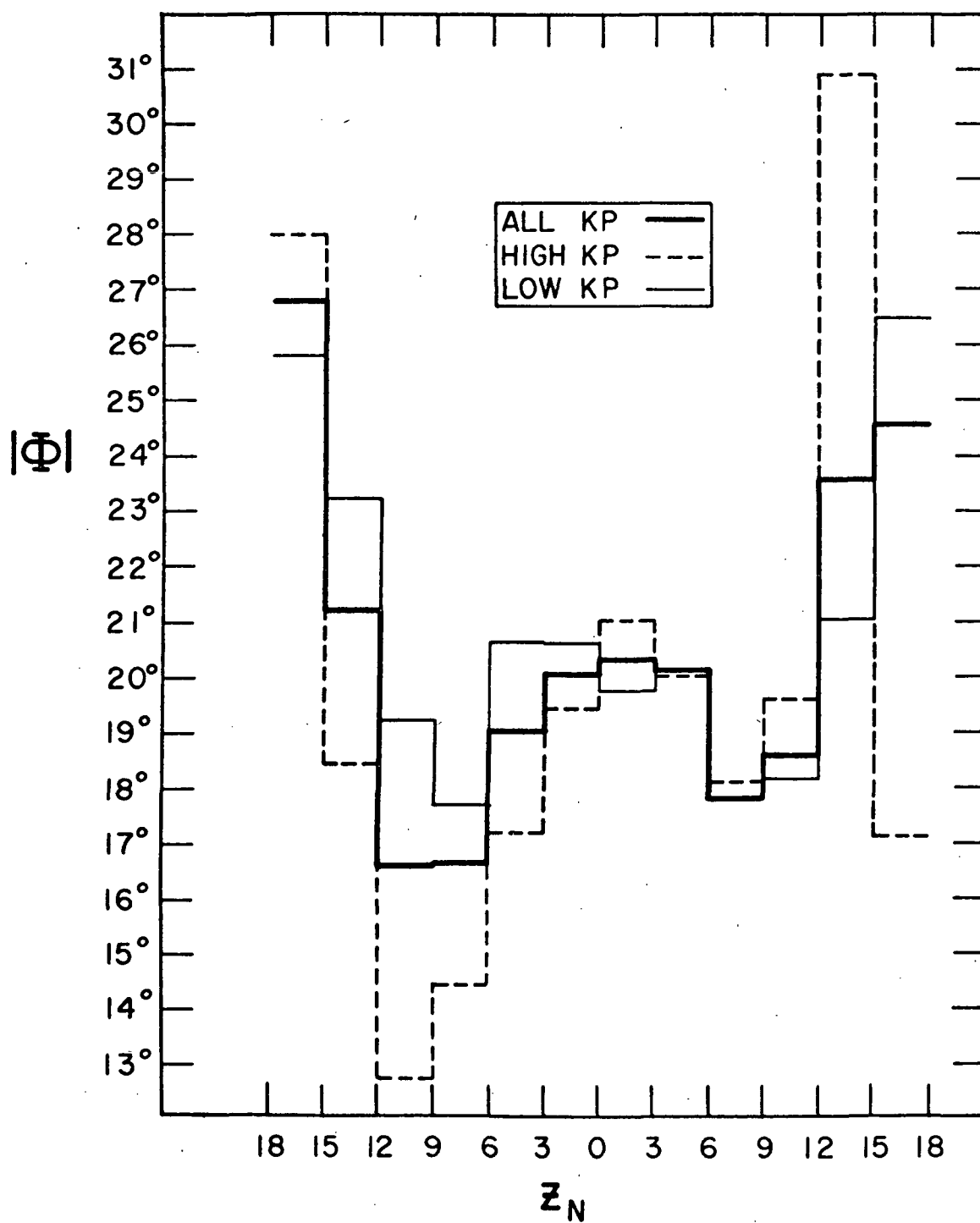


Figure 14
(cont.)

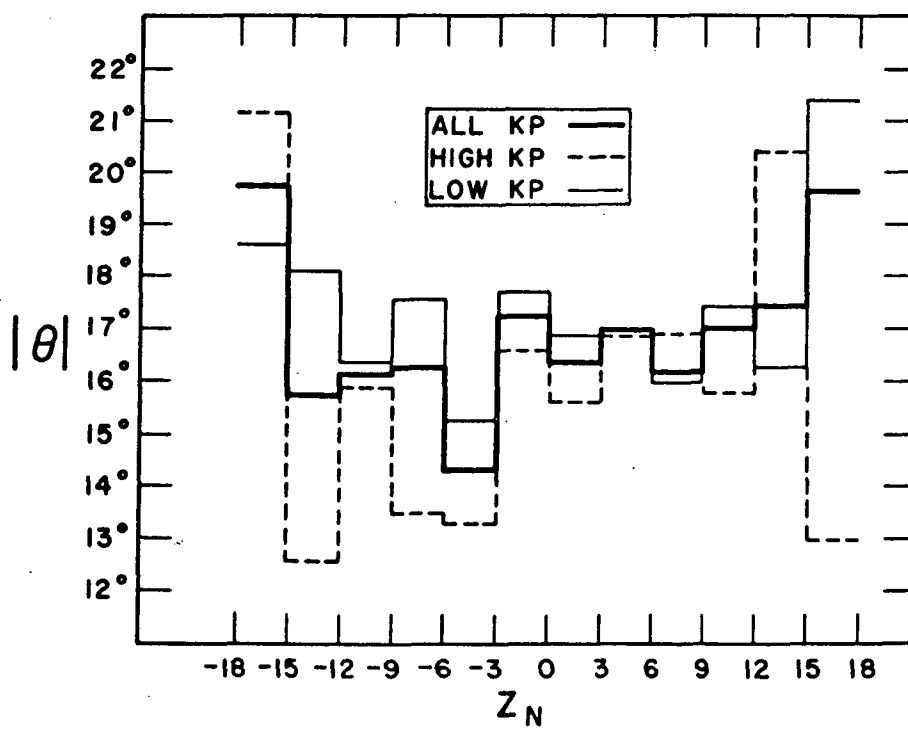
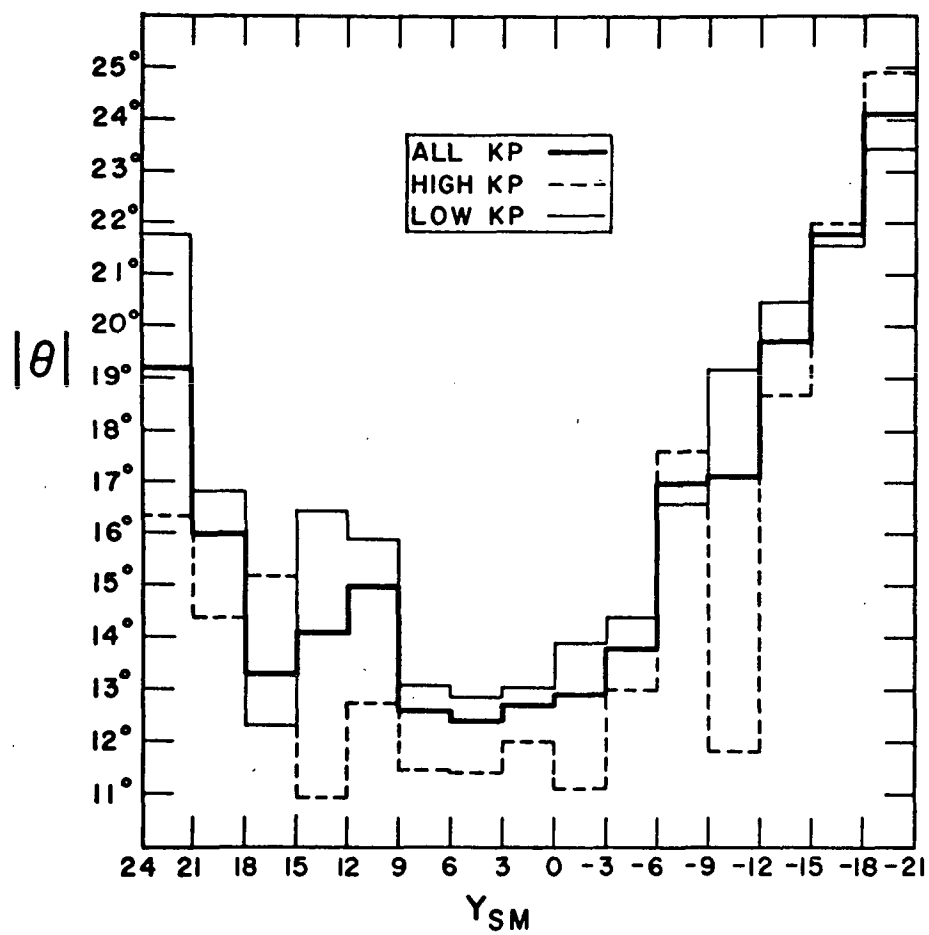


Figure 15

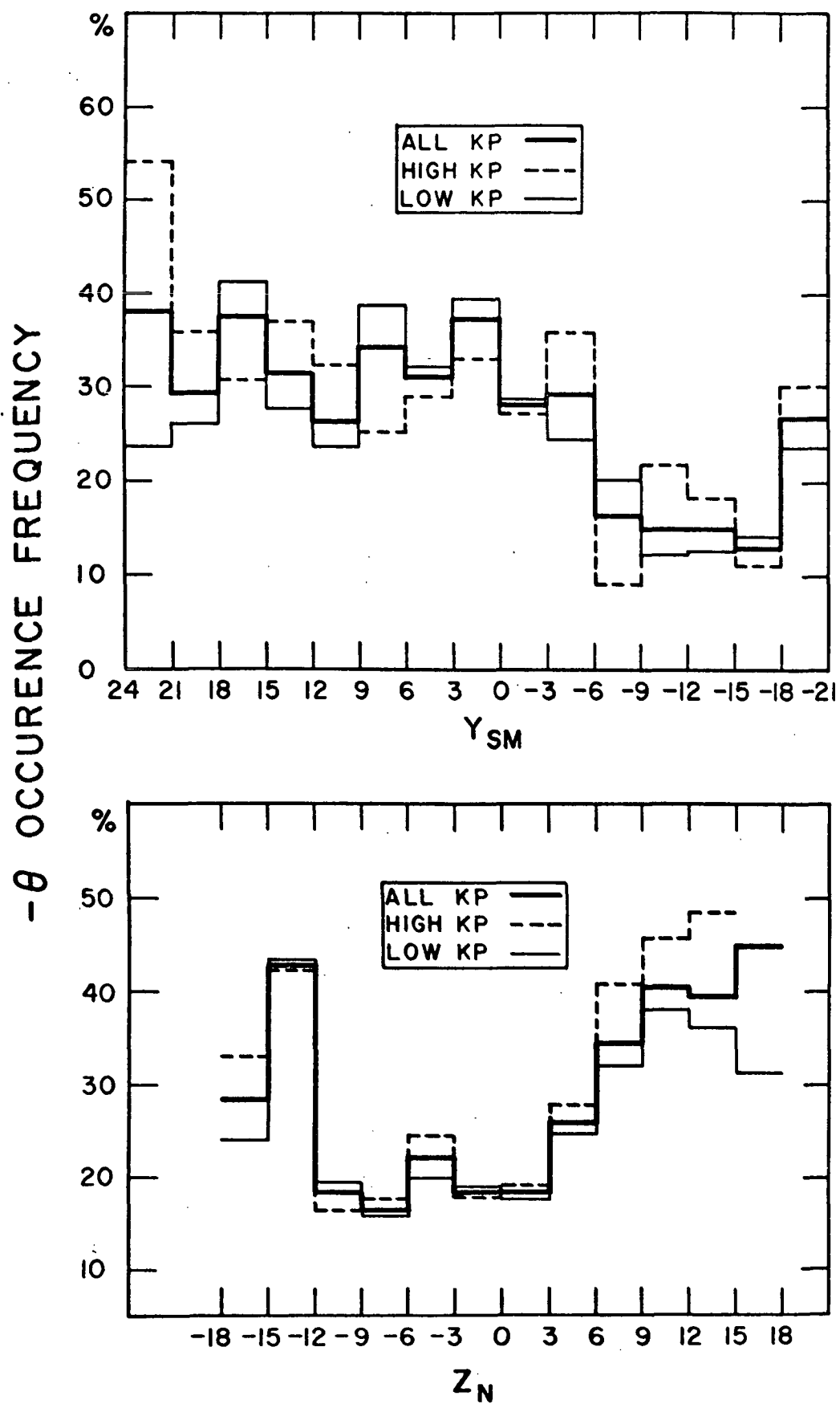


Figure 16